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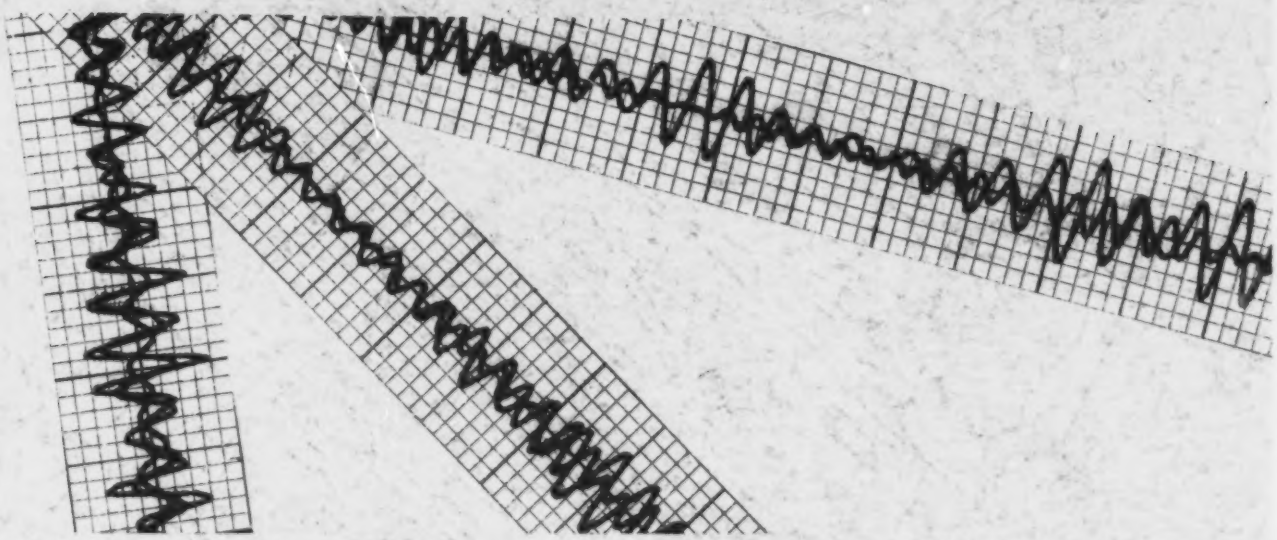
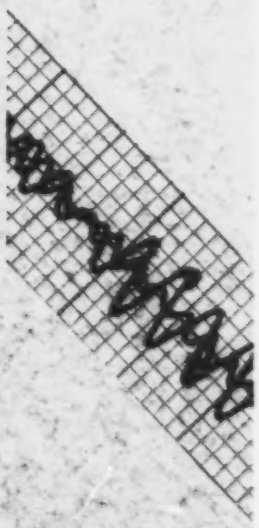


HYDRAULICS LABORATORY

Laboratory Technical Report

THE SWIFTSURE PRINCE HAWSER STUDY

MODEL CONSTRUCTION AND INSTRUMENTATION



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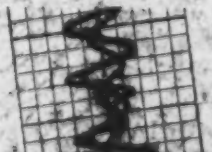

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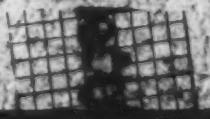

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THE SWIFTSURE PRINCE HAWSER STUDY

MODEL CONSTRUCTION AND INSTRUMENTATION

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SUMMARY

This report details the construction of the 1:48 scale physical model of a portion of the New Westminster section of the Fraser River, the barge Swiftsure Prince, and instrumentation to create resultant wind forces and moments on the moored barge, to simulate the force versus elongation behaviour of the hawsers or mooring lines, and to measure the forces in the lines. In addition to the Swiftsure Prince, models to the same scale of the Forest Prince, the Grecian Legend, the Patullo Bridge and the New Westminster railway bridges were also constructed.

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1.0 INTRODUCTION

On December 26, 1975, just after 2 p.m., the self-dumping log barge "Swiftsure Prince" broke loose from her moorings at berth 4 at Pacific Coast Terminals, New Westminster. The moderately strong wind then blew the vessel upriver where it knocked down the 380 ft north span of the railway bridge. The barge continued upstream and was eventually taken in tow by a tug.

The Hydraulics Laboratory of the National Research Council of Canada (NRC) in Ottawa, has for several years been studying the moored behaviour of large vessels. The physical model results from the test basin under the action of regular or random sea states have been compared with predictions from a numerical mathematical model developed in Hawaii. Rather sophisticated instrumentation was developed for simulating the stretchiness or non-linear force versus elongation characteristics of mooring lines. Other devices were developed to measure the force in the lines, and the ship movements. This technology was found to work very well, and was directly transferable to the Swiftsure Prince mooring line study.

Although mathematical models exist to calculate vessel static mooring line forces under the action of wind, waves and current, very few comparisons with forces on real ships or even on physical models, have been made. Espe-

cially in the case where there are varying forces on the ship (e.g. due to wind gusts) little confidence has been inspired through the use of mathematical models. Therefore, although several people will be estimating the forces in the lines of the barge Swiftsure Prince using mathematical models, it was decided to construct a physical model in addition. Far fewer assumptions and estimates have to be made with physical models, the results are more accurate, and the visual impact or impression on the observer is far more convincing.

1.1 Scaling of the Physical Model

Photo 1, and Figs. 1 and 2 show the extent of the Fraser River at New Westminster which was modelled. The model scale was 1:48 in both horizontal and vertical directions. The model boundaries are from 1800 ft downstream of the bend or knee in the dock near berth 4, to about 3000 ft upstream of the "bend". This means the model is about 100 ft long. The model width is about 44 ft, representing over 2100 ft on the river. The scale of 1:48 was chosen so that wind and hawser forces would be large enough to be measured accurately, and so turbulent flow would exist in the model as it does in the real river. For physical models with a free air-water surface, such as lakes, rivers, tidal estuaries, all textbooks on fluid mechanics and modelling

(Refs. 28, 29) show the model and prototype (real river) will have similar flow patterns (velocity and acceleration ratios) and pressure or force distribution ratios, if the Froude number of the model and prototype are the same. This means

$$(Fr) = \frac{V_m}{\sqrt{gL_m}} = (Fr)_p = \frac{V_p}{\sqrt{gL_p}}$$

where V_m, V_p are fluid velocities in model and prototype;

g is acceleration due to gravity;

L_m, L_p are lengths (or depths) of model and prototype.

(The Froude number is a ratio of inertia forces to gravity forces, and applies where water surface elevation differences (such as river slope) act to drive the flow.)

As an example, the Fraser River model section at NRC is built to a geometric scale of 1:48, so that $L_m/L_p = 1/48$. Therefore the velocity in the model from the Froude criteria above is:

$$V_m = \frac{1}{\sqrt{48}} \times V_p = \frac{V_p}{6.928}$$

The velocity ratio, V_r, between prototype and model is therefore

$$V_r = \frac{V_p}{V_m} = \sqrt{\frac{V_p}{V_m}} = \sqrt{48} = 6.928$$

Table 1

Ratios between Prototype and Model Measurements

Characteristics	Dimension	Froude Scale Ratio (= prototype/model)
Length	L	$L_r = L_p/L_m = 48$
Area	L^2	$A_r = A_p/A_m = L_p^2/L_m^2 = 48^2 = 2304$
Volume	L^3	$48^3 = 110\ 592$
Time	T	$(L_r \rho_r/\gamma_r) = (48)^{1/2} = 6.928$
Velocity	L/T	$(L_r \rho_r/\gamma_r) = (48)^{1/2} = 6.928$
Acceleration	L/T^2	$\gamma_r/\rho_r = 1$
Discharge	L^3/T	$L_r^{5/2} (\gamma_r/\rho_r)^{1/2} = 48^{5/2} = 15\ 962.6$
Mass	M	$L_r^3 \rho_r = 48^3 = 110\ 592$
Force	$ML/T^2=F$	$L_r^3 \gamma_r = 48^3 = 110\ 592$
Density	M/L^3	$\rho_r = 1$
Specific Weight	$M/L^2T^2=F/L^3$	$\gamma_r = 1$
Pressure	$M/LT^2=F/L^2$	$L_r \gamma_r = 48$
Impulse and Momentum	ML/T	$L_r^{7/2} (\rho_r \gamma_r)^{1/2} = 48^{7/2} = 766\ 203.9$
Energy and Work	$ML^2/T^2=FL$	$L_r^4 \gamma_r = 48^4 = 5\ 308\ 416$
Power	$ML^2/T^3=FL/T$	$L_r^{7/2}/\gamma_r^{3/2}/\rho_r = 48^{7/2} = 766\ 203.9$

where the length ratio $L_r = L_p/L_m = 48$. The preceding table summarizes the ratios between prototype and model characteristics for Froude Number similarity for our 1:48 model. Since water is the working fluid in both model and prototype, the density ratio ρ_r and specific weight ratio γ_r are both equal to 1. Using Table 1, one can convert from model to prototype or reverse for any of the characteristics. Note that the forces of viscosity, elasticity and surface tension are assumed unimportant compared to inertia and gravity forces related by our Froude modelling.

It must be appreciated that no model, except one the same size as the prototype, can truly reproduce complete similarity between model and prototype using one scaling law (such as Froude). Considering just the water flow in the river model, the flow patterns and velocities will scale well according to the Froude law if we keep the Reynolds number $R = Vd/\nu$ (in which V is fluid velocity, d is depth, and ν is kinematic viscosity) high enough for turbulent flow to exist, say $R > 10^3$ to 10^4. In our 1:48 scale model, the flow Reynolds number for a velocity of 0.3 fps (2 fps prototype) and a depth of 0.8 ft (38 ft prototype) is

$$R = \frac{0.3 \times 0.8}{1.1 \times 10^{-5}} = 2.2 \times 10^4,$$

which is sufficient to ensure turbulent flow. Then water forces on blunt-shaped objects in the flow will scale properly according to the Froude scale laws.

However, if we now consider the 1:48 model of the Swiftsure Prince hull docked at berth 4, water current forces on the stern and on the twin skegs or fixed rudders may scale properly, but the skin friction forces along the length of the hull will not. This is because skin friction is highly dependent on shear or gradient of the boundary layer flow along the hull surface. The boundary layer thickens as the flow moves from stern to bow (for river flow moving upstream and Swiftsure Prince moored bow upstream). The Reynolds number is used to describe this boundary layer development, with $R = VL/\nu$, where L is the distance along the hull from where the flow first encounters the sides of the hull. Turbulent boundary layers have large lateral mixing, and therefore are able to follow the changing contours of the hull better than a laminar boundary layer. Ref. 30 shows the laminar boundary layer changing to fully turbulent by a Reynolds number of about 3×10^6. On the prototype hull with a 2 fps current along it, the laminar boundary layer will become fully turbulent within about 20 ft as the flow passes along the hull. The remaining wetted hull length of 275 ft will have turbulent boundary layer skin friction. Thus the hull is affected over 93% of its wetted length by a turbulent boundary layer. However the 1:48 model of the hull with 0.3 fps water velocity does not develop a turbulent boundary layer for 40 ft, and considering the model

wetted length is only 295/48 = 6.1 ft, this means a mainly laminar boundary layer exists along the entire model. A skin friction coefficient C_f as determined by drag measurements on the model hull will be larger than the more constant coefficients one would obtain for a turbulent boundary layer. Applying the model C_f to predict the full scale hull drag component due to skin friction from

$$D = C_f \rho A (V^2/2)$$

where D = drag due to skin friction

A = hull wetted area

V = water velocity

will result in predicting water drag forces on the hull which are too large.

Although one could attempt to calculate corrections to be applied to the measurements of the water current drag on the moored model of the Swiftsure Prince, this was found not to be necessary. The forces were so small compared to the wind forces as to have negligible effect on the stresses in the mooring lines. Hence all Reynolds number considerations were found to be just academic, and the river current had negligible effect on the hawser forces developed.

2.0 CONSTRUCTION OF THE FRASER RIVER MODEL

The model was constructed to a 1:48 scale using the river bed contours as given on Plan No. FR11 B-97, Public Works of Canada, Sheet 1 of 3, hydrographic survey, September 30, 1975 (Ref. 8, 1975), and also further details in Refs. 6 and 19. All water depths and dock elevations were referred to local low water datum for this chart location. This chart datum (0 ft at LLW) is 7.0 ft above an elevation of zero at Sand Heads out near the mouth of the Fraser River. The deepest point modelled is near the Patullo Bridge and is -71.5 ft. Before constructing the model, the laboratory floor was levelled (and designated -71.5 ft) using plywood shims on which the model templates would be placed. Since bottom depth changes or slopes are relatively mild, the grid spacing selected of 4 ft (192 ft) was considered sufficiently accurate to define the bottom.

Next, referring to Fig. 2, lines 1 to 27 were drawn 4 ft apart and masonite templates cut out which were nailed to the floor pads. The top of each template represents the elevation of the river bed along lines 1 to 27. Sand was placed between templates and packed to within 1 inch of the top of the templates. This inch was then filled with cement grout resulting in a hard skin representing the river bed. Accuracy of ±1/8 inch (or ±0.5 ft in the real river) is achieved at the template locations.

Between templates sharp discontinuities, ridges or holes, will not show up in the model due to the screeding process of spreading the grout. The two sediment control groins near lines 14 and 20 (see Fig. 2) are the only features which had to be surveyed-in and added by hand-forming after completion of the model skin.

The Phase III Trifurcation as-built drawings (Refs. 15 to 13). were used to locate and build these features in the model.

The dock (Figs. 2 and 5) was constructed according to drawing Refs. 11 to 13. All fender piles, and 3 rows of main dock support piles back from the fender piles, were included in the model. Considering the lower Reynolds Numbers in the model, this number of piles should create sufficient under-dock resistance to flow to simulate the real situation, which has virtually zero flow there. Additional roughness could be added between the piles in the form of screens if need be, but was found unnecessary. The immediate under-deck construction was not simulated. The deck surface elevation was surveyed by Public Works Canada as 19.48 ft above Sand Heads datum, on September 3, 1980 by R.F. Richardson.

No provision was made for water to move down the river since at the time of the accident upriver flow occurred. This tidal driven flow (with a wind driven component

also) was admitted to the model through a manifold of holes across the downstream boundary. Very smooth flow input conditions were achieved. The flow itself came from a constant head tank supplied by a large pump.

At the upstream boundary of the model, just past the Patullo Bridge and New Westminster railway bridge (the piers of which were cast into the model) the flow discharge passes over a 10 ft wide weir and finally to the Laboratory sump. This weir is adjustable to 0.001 inch accuracy, and serves to maintain a steady water level in the model independent of the flow discharge. Thus for high flows moving upstream, the weir was lowered to maintain the correct water level at the dock. This water elevation was supplied in Ref. 21 from Water Survey of Canada, as measured by a water level recorder (08MH025) which was located on the wharf within a few feet of the Swiftsure Prince. For the time of the accident, about 1410 hours, December 26, 1975, the water elevation was 14.68 ft above Sand Heads datum (or 19.48 - 14.68 = 4.80 ft below the dock deck surface). As mentioned in this same Ref. 21, this level is about 1.5 ft higher than predicted, due most likely to the strong wind which was blowing up the river. This wind was not local in character since it raised water levels at other stations (e.g. Port Mann and Pt. Atkinson) along the river. It can be shown that this same water level rise could not have been produced

by a corresponding rise at Sand Heads or the Strait of Georgia. The rise at those places only confirms the general areal extent of the strong winds.

2.2 Construction of the Swiftsure Prince Barge Model

From the plans of the barge by Robert Allan Ltd., Refs. 2 and 3, and the as-fitted arrangement by Yarrows Ltd., Ref. 4, a wooden "plug" was carved from pine, to a scale of 1:48. Then a female fibreglass mould was cast around the "plug". When separated, a male shell of fibreglass cloth and resin was laid up inside the mould, and removed when cured to become the model hull of the Swiftsure Prince. Surface finish and accuracy are smooth and excellent, and unlike wooden hulls which may swell, the fibreglass hull can remain in the water indefinitely for the test series. Fig. 4 and Photos 2 and 3 show the barge model.

The deckwork, log stop 'walls', cranes, bollards and fairleads were all simulated more for appearance than for authenticity. Estimates were made of the longitudinal and vertical distribution of vessel weight in order to place ballast correctly to achieve the unloaded waterline condition shown on Public Works Canada drawing July 1980, Ref. 1, Fig. 4 This drawing shows the vessel to draw 5 ft near the bow, and 6 ft near the stern in its unloaded condition. Experiments were carried out on the model by Western Canada

Hydraulics Laboratory personnel to correctly obtain the required polar moment of inertia, centre of gravity, etc.

The twin skegs (fixed rudders) were placed according to the plans and adjusted so the vessel tracked truly when towed ahead.

Below deck, instrumentation was mounted which allowed the model mooring lines or hawsers to simulate the force versus elongation characteristics assumed for the real lines just before the accident. The lines themselves exit from the barge at exactly the same locations as the open and roller fairleads on the real vessel. The friction in, and sharp curvature of the line in passing through the real fairleads was not simulated in the model.

2.3 Construction of the Forest Prince, Grecian Legend and Bridges

Wooden models of the Forest Prince, the Grecian Legend, and the two bridges, were made, Photo 1. The major dimensions of these models are correct, but detail accuracy is not claimed. These models merely give scale to the overall physical model and are intended for observers of photographs of the model to orient themselves.

The two vessel models, the Forest Prince and Grecian Legend may also serve another more technical purpose. They supply the appropriate "blockage" to the river flow

moving along the dock. Moored at the correct location along the wharf, and at approximately the correct draughts (assumed as 6 ft for the Forest Prince, and 25 ft for the Grecian Legend), they would recreate the proper velocity field acting on the Swiftsure Prince model if it were to be "blown" or caused to move upriver past them towards the New Westminster Bridge. Errors in the assumed draughts of the two vessels would not significantly affect the Swiftsure Prince's path, since the upstream river velocities were found to be low even when the effect of the wind on the water surface layers was considered. In fact it was found later in the test programme that movement of the Swiftsure Prince up the river was not really required as the accident was already being caused when the barge breaks free of its moorings.

3.0 MODEL INSTRUMENTATION AND CALIBRATION

Water flow into the model is supplied by a constant head tank, through a valve and pipe, and into a manifold or perforated subfloor which distributes the flow across the width of the river. The water quantity was sensed by a Polysonics Ultrasonic flowmeter attached to the delivery pipe.

Basically either of two flow rates could be run on the model. Western Canada Hydraulics Laboratory (WCHL) with

the aid of a mathematical tidal model of the Fraser River, and with their 1:480 horizontal, 1:72 vertical scale physical model, in their Port Coquitlam laboratory, determined the flow rate and velocity distribution horizontally and vertically for the New Westminster reach of the river.

The first flow rate or upstream discharge was found to be about 70 000 cfs (or 4.4 cfs in the model) assuming no wind effect on the velocities. Running this flow in the model, distributed blockage in the form of spaced concrete blocks and metal guidevanes, were used to obtain a lateral distribution of velocity across the model the same as predicted by the WCHL physical model. The velocities were measured using a Marsh-McBirney Co. electromagnetic velocity probe. The velocities in the model for this low flow rate situation were small, and would contribute very little to forces developed in the mooring hawsers.

The second flow involved estimating the effect a 25 mph wind (an assumption made for the purpose of this study) would have on the water velocities. The water surface layers would move under the action of wind at about 3% of the wind speed. This speed 1.1 fps (0.16 fps in model) was added to the first (or low) flow rate generated velocities to obtain estimates of the water currents which likely existed at the time of the accident. These currents required a higher flow rate to be run in the model to prod-

uce the required currents. Details of the flow or current calibration are contained in the report by WCHL. Again it was found that even these currents resulted in drag forces on the model hull which were very small compared to the forces exerted by the wind.

Water levels were measured in the river model at the flow input end and near the outlet weir by point gauges and also by twin-wire capacitance water level sensors, to within 0.005 inch accuracy.

The 10 ft weir upstream of the New Westminster railway bridge was used to adjust the water level at berth 4 to 14.68 ft referred to Sand Heads datum existing at the time of the accident sequence.

A grid made up of lines 2 ft apart (96 ft prototype) painted on the model bed allowed locating water velocity profile sections, timing barge movements, and dye cloud tracks. A "catwalk" some 24 ft above the model permitted observations and photographs to be made from above.

3.1 Mooring Line Simulators

Photos 2 to 5 show the devices used to model the force versus elongation (stretchiness) behaviour of the four mooring lines on the Swiftsure Prince. There are four perspex plates mounted, two forward and two aft below the barge deck level. On each plate is a cantilever spring, a rectan-

qular cross-section bar of spring steel (1 x 1.5 mm) of suitable and variable lengths. The mooring line, a relatively strong length of 15 lb test nylon fishing line, leads from the free end of the cantilever spring, through ball bearing guide rollers or glass-lined ferrules at the location of the fairleads on the barge, over to the cleat and bollard locations on the dock. There the line passes through guiding eyelets to a dynamometer which measures the force or pull in the hawser. Figs. 10 to 13, and Figs. 16 to 19 show the hawser force versus elongation characteristic curves derived for testing. Notice how the curves show the line to become stiffer (i.e. stretch less) at higher forces. This effect is achieved by having the cantilever spring steel bar on the barge perspex plate deflect easily at first, but then as it encounters carefully located brass pins, it effectively becomes a progressively shorter, and therefore stiffer, cantilever spring. We can simulate the non-linear force-elongation characteristics very well by this virtually inertia-free device, Photo 4.

Cantilever springs and mounting plates were calibrated to simulate two different assumed force versus elongation behaviour curves for 2 inch nominal diameter monofilament polypropylene mooring lines. The first simulation was made assuming the lines to behave as "new" or "lightly-used" ropes. Fig. 8 shows curves from British Ship Research Asso-

ciation (Ref. 26). Appreciating that multi and monofilament polypropylene ropes give essentially the same curve, it was decided to use curve (3) from Fig. 8 to represent "new" lines. Breaking strength was taken as 48 000 lbs, and the curve is plotted as Fig. 9.

Obviously the line on-board the Swiftsure Prince was not "new", but such a new-line characteristic curve gives an upper bound for the possible strength and elasticity of the lines. Figs. 10 to 13 show the simulators duplicated the desired curve very well.

For lines which have undergone <u>severe service</u>, and have had say 120 consecutive loadings to 50% of their breaking strength (48 000 lbs = F_B), followed by 1 hour's rest, a significant permanent or "residual" elongation occurs. They will then no longer have much stretch left before they will break. They will likely break at considerably less than the F_B of 48 000 lbs due to strain and friction heat buildup over fairleads, etc. However, to be conservative, it was assumed the 48 000 lb strength could still be developed by a "severely-used" rope under static strain conditions (i.e. slowly applied loads). If the load were applied suddenly as by surging of the barge due to wind gusts, then forces in the mooring lines of up to 2 to 3 times could be generated. These dynamic suddenly-applied loads are difficult to estimate mathematically, but with the physical model in which

the mooring characteristics and vessel inertia are scaled, some meaningful measurements can be obtained.

Using, Fig. 14 of Ref. 27 and interpolating Fig. 15 was obtained as approximating the force versus elongation behaviour expected of a "severely-used" 2 inch polypropylene rope. Picking off in Fig. 15, for various F/F_B values, what the corresponding $\Delta L/L_o$ values are, then F and ΔL are calculated for F_B = 48 000 lbs, and L_o is taken from Table 2. This results in the curves in Figs. 16 to 19. The points represent a sample system calibration check which is excellent for the two bow lines (Figs. 18 and 19) but shows the two stern lines in the model are slightly soft (Figs. 16 and 17), i.e. tending toward ropes in newer condition. The true behaviour curve of the lines on the Swiftsure Prince probably would lie somewhere between the "new" rope and the "severely-used" rope curves. By testing with both situations, one can bracket the probable barge behaviour and stresses generated during the break-away and accident of December 26, 1975.

Based on instructions of Counsel as to the lengths of mooring lines recovered after the accident and their places of use on the dock and on-board the barge, and the location of the Swiftsure Prince when tied up (Examinations for Discovery), I have estimated the following two barge mooring positions. For the barge as tied up at approxi-

Table 2

Mooring Line Lengths as Tied up December 20, 1975

at 0415 hrs

Line No.	Straight length, no sag L_o (ft)	
1	Stern capstan to roller fairlead =	6
	and then to cleat #5 =	71
		77 Total
2	Stern starboard bollard to fairlead =	4
	then to cleat #6 =	71.2
		75.2 Total
3	Bow port bollard to fairlead =	5
	then to bollard #52 =	84.9
		89.9 Total
4	Bow starboard bollard to fairlead =	5
	then to bollard #52 =	102.7
		107.7 Total

The following tie-up possibilities were not felt to be consistent with the lengths of broken bow lines recovered.

5	Bow port bollard to fairlead	5
	then to bollard #51	44.6
		49.6 Total
6	Bow starboard to fairlead	5
	then to bollard #51	73
		78 Total

mately 0415 hrs, December 20, 1975, 1.5 hours after low tide, the tide level was about 6.75 ft, and currents along the berth were almost zero (slack water). Thus no strain on the mooring lines was being introduced by the currents at tie-up. Fig. 5(a) shows the assumed position, line arrangements and lengths at 0415 hrs, December 20, 1975. The line

lengths include the distances from dock cleat or bollard to fairlead, and then to on-board bollard or capstan, assuming no sag due to the weight of the line. Table 2 summarizes the line lengths for the as-tied-up situation. Appendix I shows how the line lengths were calculated.

Fig. 5(b) shows the line lengths L for the barge on December 26, 1975 at 1400 hrs, just before the accident. Again, Appendix I contains the calculations of these lengths.

Figs. 6 and 7 locate the bollards, cleats and fairleads in elevation views looking downstream towards the stern, for both the tie-up (0415 hrs, December 20, 1975) and the before-accident (1400 hrs, December 26, 1975) conditions. Note the 4 ft stand-off of the hull from the dock cleat at tie-up due to the fender piles.

3.1.1 Line Pretensions

The lengths L_o given in Table 2 include no sag due to the weight of the line itself. The lines would have a sag at their mid-length of about 2 to 4 feet. The line weighs about 1040 gm/m or about 50 lbs total for each stern line, and approximately 60 lbs for each bow line. This creates a small stretch in each line of 3 to 4 inches, and produces a tension in the lines of some 300 to 400 lbs. This tension of course acts on the dock bollards or cleats

as well as the barge, holding it against the fender piles. Appendix 2 describes this in more detail.

Next consider from Appendix 1 the condition of the lines at 1400 hrs, December 26, 1975 just prior to the barge breaking loose. The water level has risen from 6.75 ft to an elevation of 14.68 ft, a rise of 7.93 ft. This stretches the lines to total lengths L_1 (see Fig. 5(b)), and generates approximate forces, F, in the lines as given in Table 3. Notice how relatively small these line tensions are. Small variations in the lengths L_o, or tensions originally assumed would have only a very minor influence on the forces in the lines when compared to the large forces generated due to wind drag on the barge. The forces in the lines are thus negligibly affected by the tide level changes experienced by the barge.

Table 3

Line Lengths and Tensions at 1400 hrs
December 26, 1975 (no wind or current)

Line	L_1 (ft) (Fig. 22)	$L_1 - L_o$ (ft)	$\frac{L_1-L_o}{L_o} \times 100$	$\%F_B$ (Fig. 9)	$F = \%F_B \times 48\,000$ (lbs)
1	78.9	1.9	2.47	4	1920
2	75.9	0.7	0.93	1.3	625
3	91.3	1.4	1.56	2	960
4	108.9	1.2	1.11	1.5	720

(L_o from Table 2; F_B = 48 000 lb assumed)

With no wind or water currents acting on the barge, the mooring ropes could experience the tension forces given approximately in Table 3 in addition to the assumed 300 to 500 lb forces in the lines when originally tied up. Therefore due only to water level rise, the lines could be under 1000 to 2000 lb tensions. These values could be slightly different if more or less slack were in the lines at initial tie-up. In the model testing program of the Swiftsure Prince, these pretensions of the lines can be varied to see what effect initial tie-up tensions may have on the final forces in the lines when the barge is being pushed by wind and water currents. However, it may be stated here that small variations in the assumed original line lengths L (Table 2) or in the original tie-up line tensions, and changes in the tide levels from 6.75 ft to 14.68 ft, the forces developed in the hawsers will be small compared to the large forces the wind drag on the barge is able to create.

3.1.2 Line Breaking Strengths

It is not known at what tensions the various lines would have broken. These strengths depend on the line condition, splices, eyes, fairlead smoothness and radius of curvature, shock loading, pretensions, etc. To enable the dynamic simulation of the breaking sequence as the stern

lines break or pull out, the stern swings out, the barge surges forward and breaks the bow lines (or variations on this scenario), each line can be "broken" instantly by a special hot-wire cutter. This cutter is mounted on the dock inside the dynamometer (Photo 5) which measures the forces in the lines. The cutter creates no extraneous drag on the line, and thus causes no errors in measuring the hawser forces. When the force (voltage) sensed by the dynamometer reaches a predetermined breaking strength value (such as 10, 20, 30, 40 or 48 000 lbs) then the on-line computer commands the hawser to be cut, and the barge becomes free to move and act on the next mooring line. Each line can be cut at whatever force the experimenter decides.

3.1.3 Mooring Line Dynamometers

To measure the forces in model mooring lines, the Hydraulics Laboratory developed several years ago the force transducer shown in Photo 5. It consists of an iron core suspended by two stiff steel springs. Tension in the mooring line pulls the core and its movement is measured by the voltage induced in a DCDT (Direct Current Differential Transformer) coil surrounding the movable core. Fig. 20 is a typical calibration line. The voltage is sent to the HP1000 Hewlett-Packard on-line computer for analysis, storage, or action (such as triggering a 25 amp pulse to the cutter hot-wire).

The dynamometer is calibrated each day to ensure its stability. To do this three known weights are hung on a special line over a pulley to give a low, medium and high force (weight) versus voltage calibration. The computer then fits a straight line to these test points enabling interpolation for forces indicated by any other voltages.

A slide on which each force transducer is mounted permits the transducer (with attached mooring line) to be slid backwards, deflecting the cantilever spring on board the barge by the same amount, and producing a voltage (or force) read by the transducer. By this means, the force versus elongation characteristic of the mooring line system as a whole can be calibrated.

These force transducers or dynamometers are also useful for measuring the pull of a string to a point on the barge deck where the resultant wind force was found to act from the wind tunnel study also carried out at the National Research Council (NRC) in the Low Speed Aerodynamics Section. With the dynamometer mounted on a screw-type translator, the wind-force string may be tightened until the dynamometer reads the desired resultant wind force. The other four dynamometers holding the mooring lines can then be sampled by computer, and the forces read and plotted out. This was done for a range of wind resultant forces and directions to find the mooring line forces developed under static conditions (no wind gusts).

3.2 Wind Force Simulation

For the time of the accident, the wind magnitude and gustiness is not known for certain as no anemometer was located at berth 4. However, from the wind records from Vancouver International Airport it is known that the wind was from the southwest (~210°), blowing at 25 mph, and gusting considerably higher. For this study it has been assumed that similar mean wind conditions would exist at berth 4. Fig. 5(a) shows several wind directions (0, +30, -30°) relative to the dock face, corresponding to 230°, 260°, 200° true wind directions.

The NRC wind tunnel model tests produced resultant wind forces on the Swiftsure Prince in the form of tables locating the resultant point of action with respect to the longitudinal and mid-length centrelines of the barge (see Fig. 21). If a string were attached at this x_o, y_o location, and pulled at a certain angle relative to the vessel fore and aft centreline, then the correct net wind force and moment (about mid-length) would be created. The wind tunnel results actually supply a "resultant force" coefficient C_R, which when inserted into the formula

$$F_R = C_R \rho A (V^2/2),$$

gives the resultant wind force F for whatever wind velocity V (fps) one chooses. With the constants ρ=0.00238 slugs/ft^3 air density, A=23 350 ft^2 barge deck plan area, the formula becomes:

$$F_R = C_R V^2 \times 27.787 \text{ lbs}$$

On board the barge model, Photo 6, a rotary potentiometer is mounted and can be placed at any x_o, y_o position demanded by the wind tunnel results. Above and attached to this "pot" is a vertical shaft with a horizontal fishing rod or guide to which the wind force string is attached. The string direction is sensed by the alignment of the fishing rod and a voltage is outputted by the potentiometer. This is the angle shown in Fig. 21.

The string leads to a carriage on a 20 ft track located near the bridges for Photo 7, but movable anywhere. The carriage, under computer command, is driven by a stepper motor to travel along the track to achieve certain angles demanded by the movement of the Swiftsure Prince model. The carriage has another stepper motor to wind in the string on a pulley to create a certain resultant wind force in this string. The actual force or tension is sensed by a DCDT force transducer below the stepper motor. The whole system is under computer control.

For a given wind velocity V and direction ψ, see Fig. 21, the wind tunnel results tell us to move to a certain x_o, y_o location on the barge deck, and to pull at angle α at the barge, β at the track, with a force determined by the formula $F_R = C_R V^2 \times 27.787$ lbs. Now, if the stern line is made to fail and the barge swings out at some angle ϕ to

the dock, this changes the wind direction relative to the barge centreline, and thus α and β must be changed under computer control. The location y_o should also be changed slightly but it was found that the error in the forces created in the mooring lines due to not varying y_o was negligible. For the static tests where no lines were caused to break, and thus the barge did not swing out, the exactly correct location x_o, y_o was used.

The DCDT force transducer is calibrated using pulleys and weights in a manner similar to that used for the mooring line dynamometers, Photo 9 A time varying force can also be produced by the computer controlled wind force simulator on the carriage to see the effect of "gusts" (or rather, unsteady resultant loads) on the dynamic response of the moored barge.

3.3 Degree of Accuracy and Limitations

The DCDT force dynamometers can easily resolve 2 gm (500 lbs) force (or 1% of the assumed breaking strength of 48 000 lbs) during the steady wind pull static tests. However when the barge is surging or moving due to the wind load being slowly or suddenly applied, or during line breakage tests, the mooring line output force trace will contain ripples which can be averaged, or the root-mean-square deviation obtained, or the peak force selected. At the computer

sampling rate of 100 samples per second, it is conceivable but not likely that an instantaneous force peak could be missed. Therefore the computer plots would if anything be conservative, and may very slightly underestimate the peak forces in the lines.

There is friction between the barge hull and the dock fender piles which is difficult to model. To minimize this friction, a pair of ball-bearing pulleys was used when appropriate (in the surging tests) to keep the hull slightly off the fender piles.

The potentiometers for measuring resultant wind force angle on the barge and on the carriage could at times (low tension in the 'wind' pulling string) be one or two degrees in error due to static friction.

The stepper motor controlling the wind force string tension works in 200 steps per revolution, and therefore unless the wind force required happens to fall within one step, the actual force produced could be slightly in error.

The cantilever spring hawser force versus elongation simulators were made to closely simulate the assumed characteristic curves for 2 inch polypropylene monofilament lines (Figs. 10 to 13, 16 to 19) but obviously could be incorect by say 1000 lbs (4 gm). This is not even considering that the actual hawsers used on the Swiftsure Prince at the

time of the accident would undoubtedly have force versus elongation characteristics (and breaking strengths) different to those assumed, likely lying between the curves for "new" and "severely used" lines chosen for this study. The study will thus bracket the hawser possibilities and it is expected that the characteristics of the real hawsers would not cause the model results to differ significantly.

The use of a result wind force location and direction from the wind tunnel study introduces some model testing complexities in that we had to be sure that small errors in x_o, y_o and height of the fishing rod pulling point above the barge deck, would have negligible effect on the mooring line forces. This was confirmed by the tests on the model by the researchers from Western Canada Hydraulics Laboratory.

In summary, appreciating the limitations of the test equipment, it is expected that the model forces measured in the various hawsers when scaled up should predict within 5 to 10% the forces the Swiftsure Prince hawsers would feel under similar conditions.

4.0 CONCLUSIONS

The main purpose of this study is to look at the static (and some dynamic forces) exerted in the mooring lines under a wide range of assumed conditions of: wind

speed, direction, "gustiness", water currents, and mooring line conditions. Once the barge has just broken free from one or two stern lines, the experiment can be considered over even though the model may not have been towed or pushed by the wind upriver into the railway bridge. Therefore we have concentrated on the breaking of the hawsers, and do not intend to be able to accurately simulate the path of the barge as it blew upstream. Too many variables (such as wind gusts with changing directions and forces, and different hawser strengths) are unknown to make it worthwhile trying to achieve this.

The important results of this study are the ability to accurately assess the static forces developed in the hawsers under various assumed wind conditions and to demonstrate the significant increase in the hawser forces if wind gusts or at least varying wind forces, caused the barge to surge against her lines. This inertia effect on shock stressing of the lines cannot be overemphasized, especially if a near-resonant condition can be creating in the mooring system. Even supertankers can be triggered to surge by very slowly varying wave groups. A relatively light barge such as the Swiftsure Prince with its massive sail-like log stops and cranes can be expected to surge at even the frequencies wind gusts may create.

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   (b) Robert Allan Ltd., After Deckhouse and Log Stop, drawing no.

   (c) Robert Allan Ltd., General Arrangement, drawing no.

   (d) Robert Allan Ltd., Forward Arrangement and Log Stop, drawing no.

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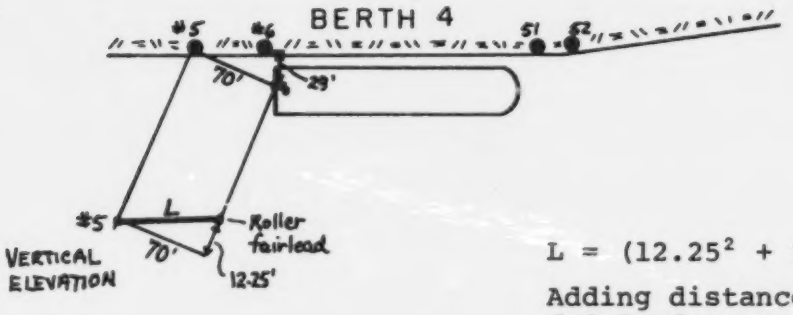
APPENDIX 1 HAWSER LENGTHS

STERN CAPSTAN LINE TO CLEAT #5

(a) As moored December 20, 1975 at 0415 hrs

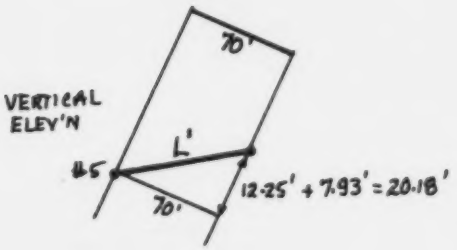


$L = (12.25^2 + 70^2)^{1/2} = 71.06'$

Adding distance of 6' from roller fairlead to capstan, total taut weightless line length is

$L_o = 77.06'$

(b) On December 26, 1975, 1400 hrs, barge is 7.93' higher



$L' = (70^2 + 20.18^2)^{1/2} = 72.85$ ft

Adding 6' to capstan

$L_1 = 78.85$ ft

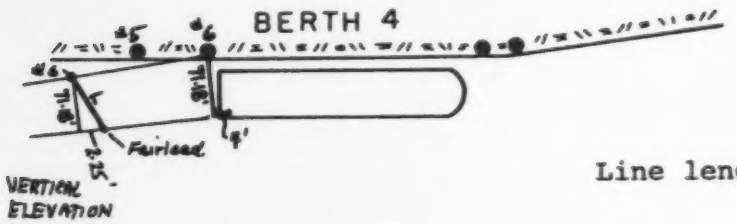
(c) The difference 78.85 - 77.06 = 1.79 ft stretch gives

$\%E = \frac{\Delta L}{L_o} = \frac{1.79}{77.06} \times 100 = 2.32\%$.

Consulting the $F/F_B \times 100$ versus $\Delta L/L_o \times 100$ curve for this line will yield F, the force in the line.

STERN STARBOARD LINE TO CLEAT #6

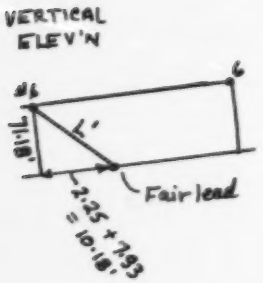
(a) As moored December 20, 1975, 0415 hrs



Line length $L = (71.18^2 + 2.25^2)^{1/2}$
$= 71.22'$

Adding 4' fairlead to deck bollard, total taut weightless line length $L_o = 75.22'$

(b) On December 26, 1975 at 1400 hrs, barge is 7.93' higher

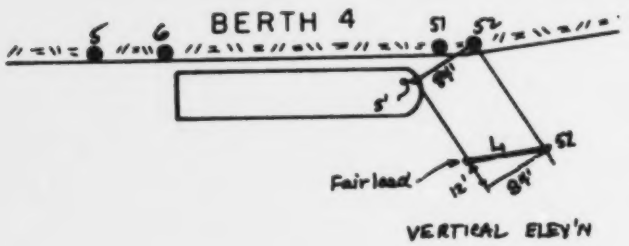


$L' = (71.18^2 + 10.18^2)^{1/2} = 71.90'$

Adding 4' fairlead to deck bollard, for total length $L_1 = 75.9'$

PORT BOW LINE TO BOLLARD #52

(a) As moored December 20, 1975, 0415 hrs

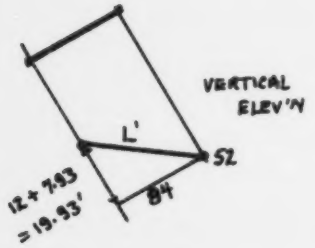


Taut line length

$L = (12^2 + 84^2)^{1/2}$
$= 84.86'$

Add 5' for distance fairlead to deck bollard, $L_o = 89.9'$

(b) On December 26, 1975, 1400 hrs, barge is 7.93' higher

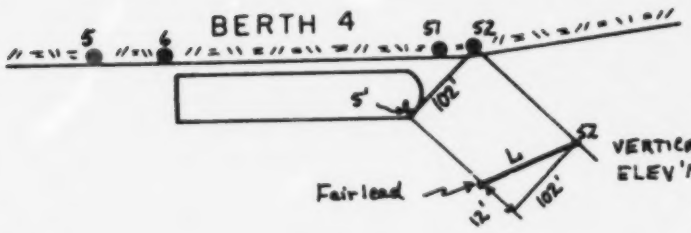


$L' = (84^2 + 19.93^2)^{1/2}$
$= 86.33'$ taut

Adding 5' fairlead to deck bollard,
$L_1 = 91.33'$

STARBOARD BOW LINE TO BOLLARD #52

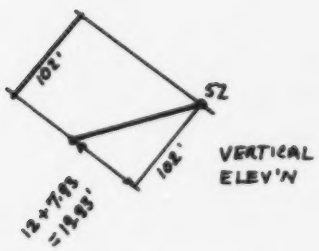
(a) As moored December 20, 1975, 0415 hrs



Taut line length
$L = (12^2 + 102^2)^{1/2}$
$= 102.7'$

Add 5' for distance of fairlead to deck bollard, $L_o = 107.7'$

(b) On December 26, 1975, 1400 hrs, barge is 7.93' higher



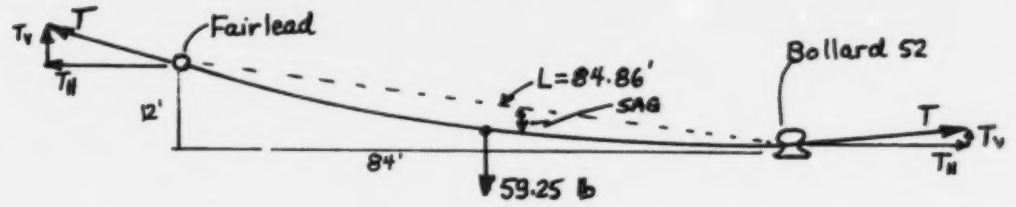
$L' = (102^2 + 19.93^2)^{1/2}$
$= 103.9$ taut

Add 5' to deck bollard

$L_1 = 108.9'$

APPENDIX 2

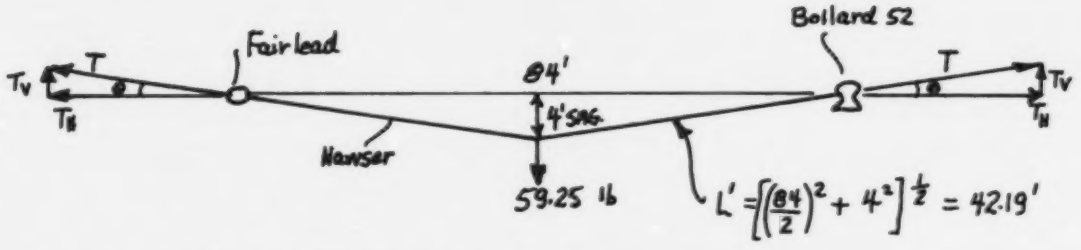
SAG DUE TO WEIGHT OF LINE FROM PORT FAIRLEAD TO BOLLARD #52



Weight of 84.86' of line $\doteq 1040 \frac{\text{gms}}{\text{metre}} \times \frac{84.86'}{3.2808} \times \frac{1}{454}$

$= 59.25$ lbs

If one allows a 4 ft sag, and assumes for simplicity the fairlead and bollard #52 are at the same elevation, then



Sum of vertical forces = 0; $59.25 = 2\ T_V$

$= 2\ T \sin\theta$

$= 2\ T \times \frac{4}{42.19}$

$T = 312$ lbs

Thus a 4' sag due to ropes' weight of only 59 lbs would require a tension of 312 lbs to be exerted at the bollard when the rope handler is tightening the line.

Note how a substantial sag of 4' only gives rise to a line length of 2 x 42.19 = 84.38 ft, just 0.38 ft more than the taut distance of 84' for a weightless line.

CURRICULUM VITAE

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  c) Pointe Sapin Harbour Model Study; wave agitation and sediment transport
  d) Energy Extraction from River Currents
  e) Calibration of flow devices
  f) Construction of Ice Chamber in Hydraulics Laboratory
  g) Ice Forces on Structures
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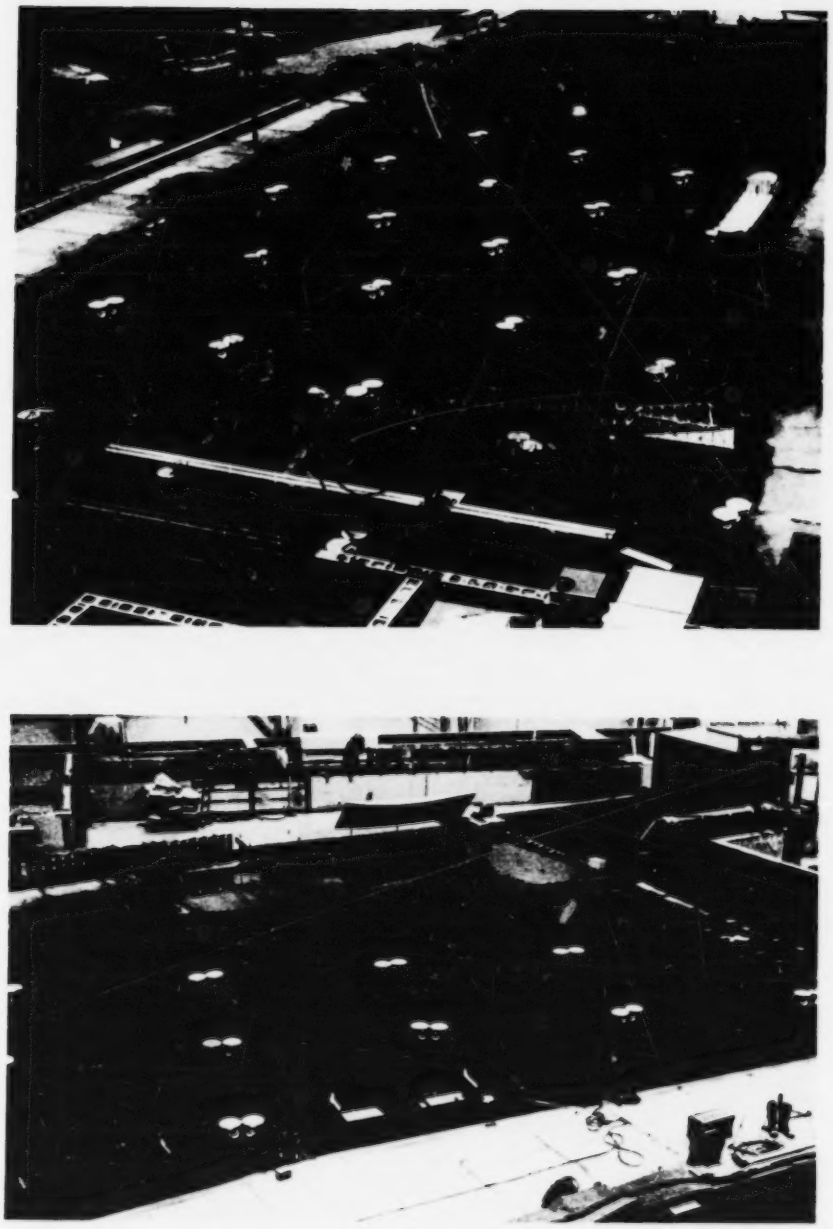
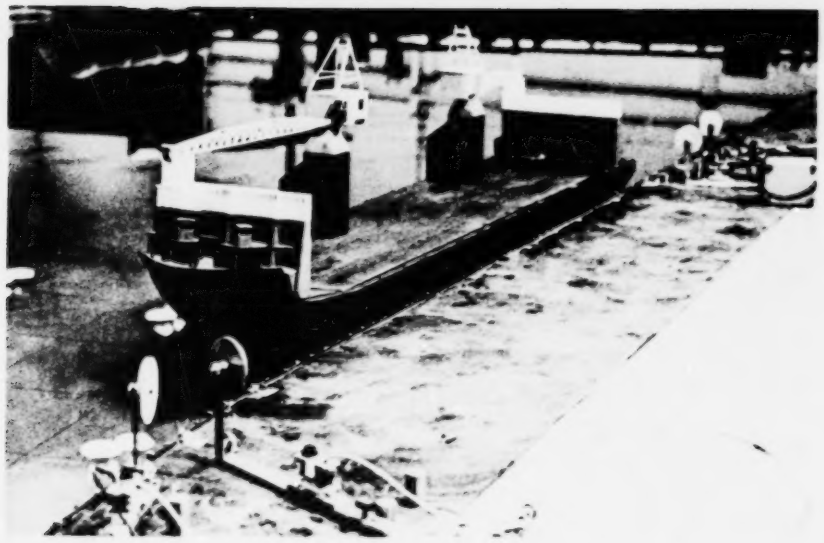


PHOTO 1 The New Westminster Section of the Fraser River
1:48 Scale Model at N.R.C.



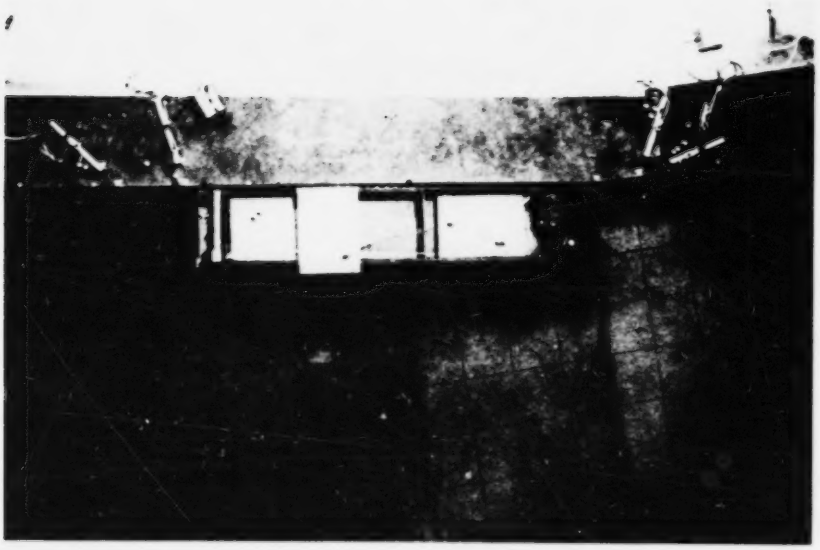


Photo 2 Swiftsure Prince Model Moored at Berth 4

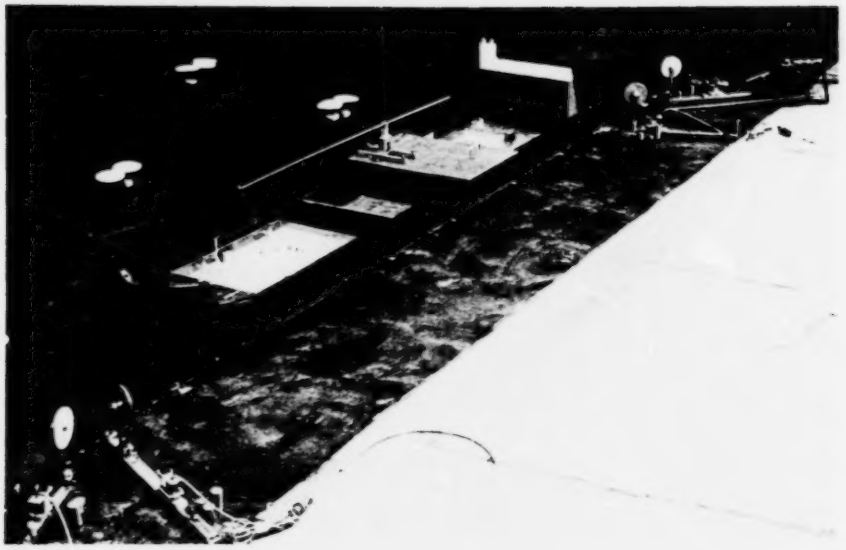


Photo 3 Mooring Line Simulators and Force Transducers for Swiftsure Prince

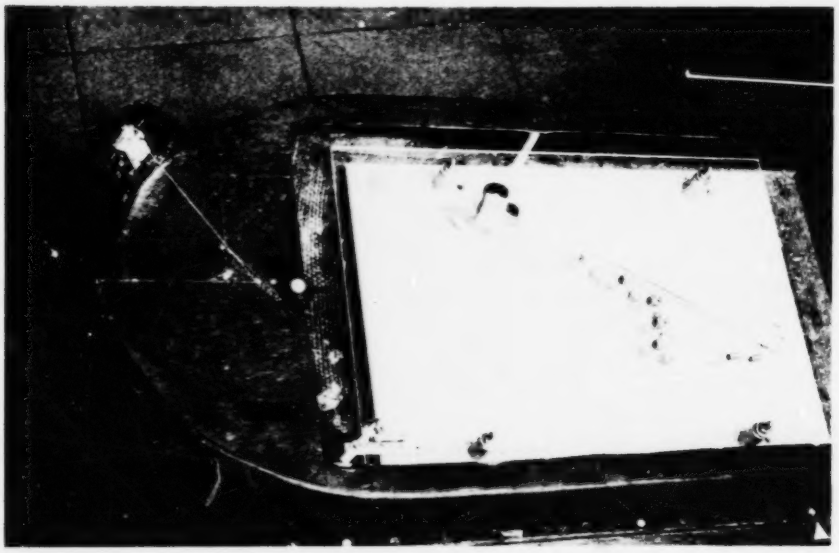


Photo 4 Load versus Elongation Mooring Line Simulator

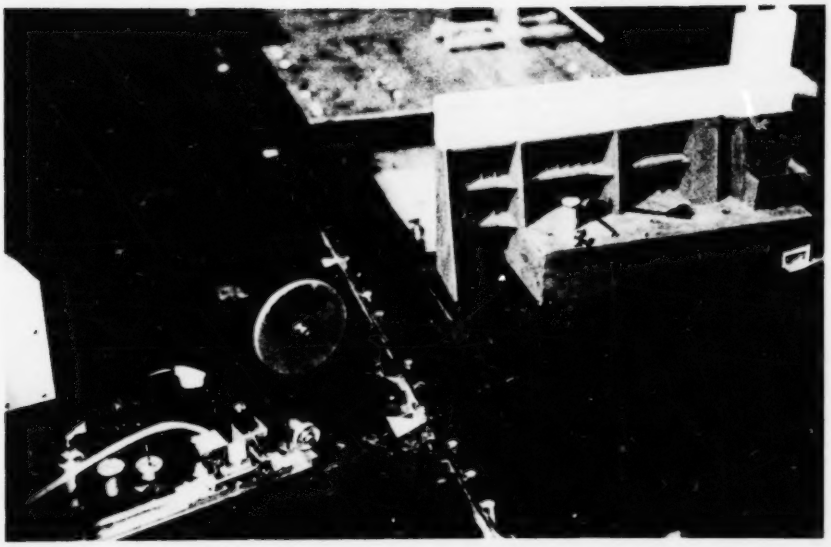


Photo 5 Mooring Line Force Transducer

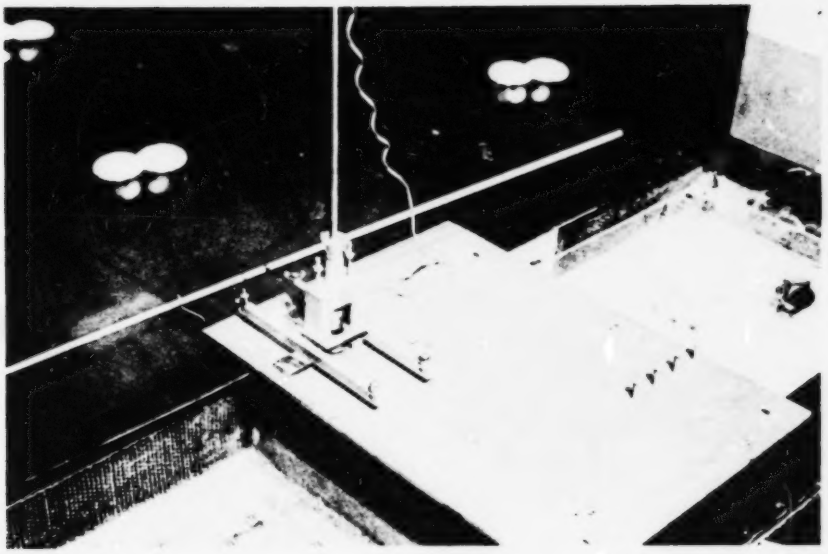


Photo 6 Resultant Wind Force Application Point and Angle Sensor

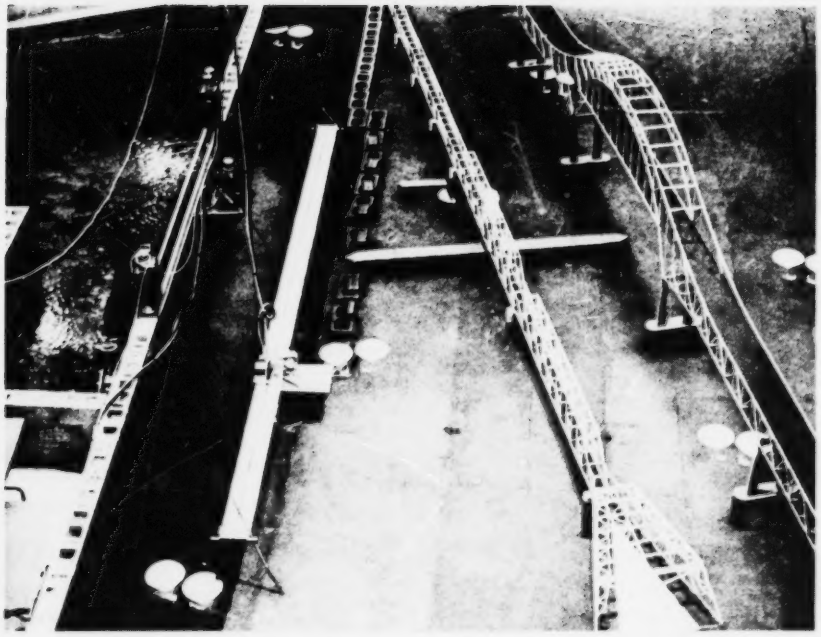


Photo 7 Wind Force Carriage, Track (and Weir behind)

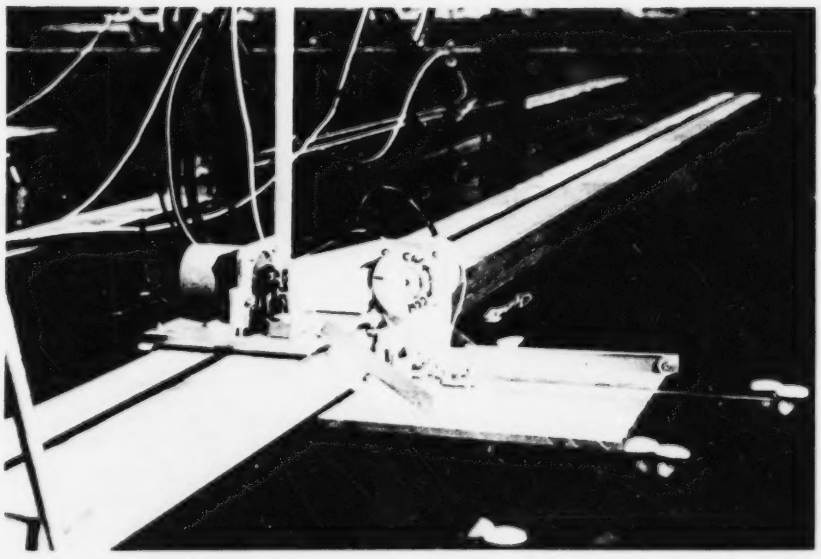


Photo 8 Computer Controlled Resultant Wind Force Transducer, Stepper Motor, Angle Sensor and Carriage Traverse Motor

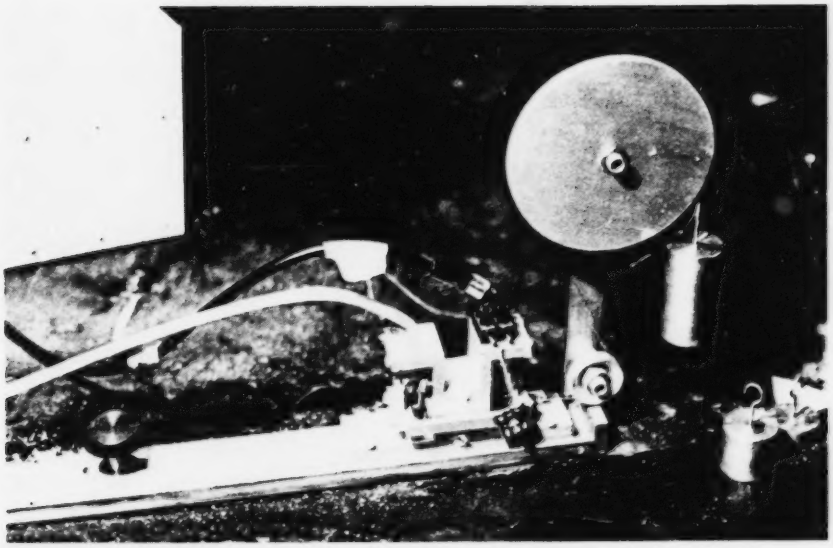


Photo 9 Calibrating Force Transducer before a Test

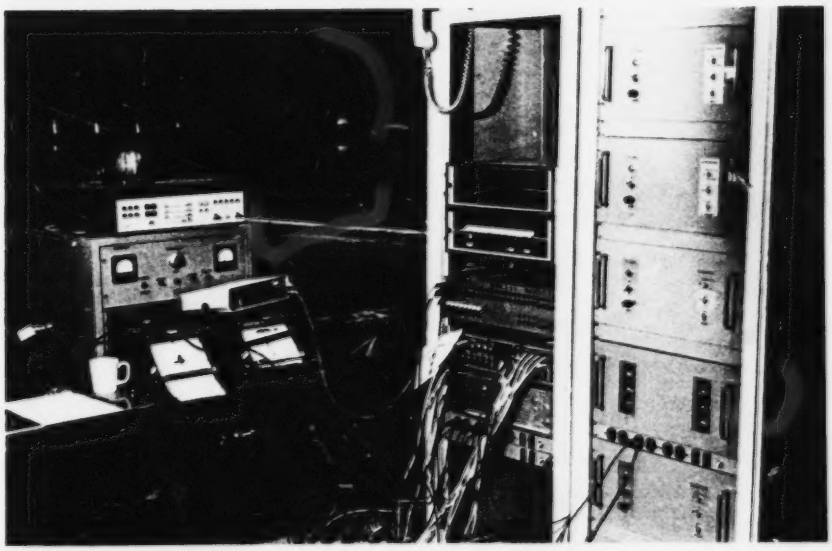
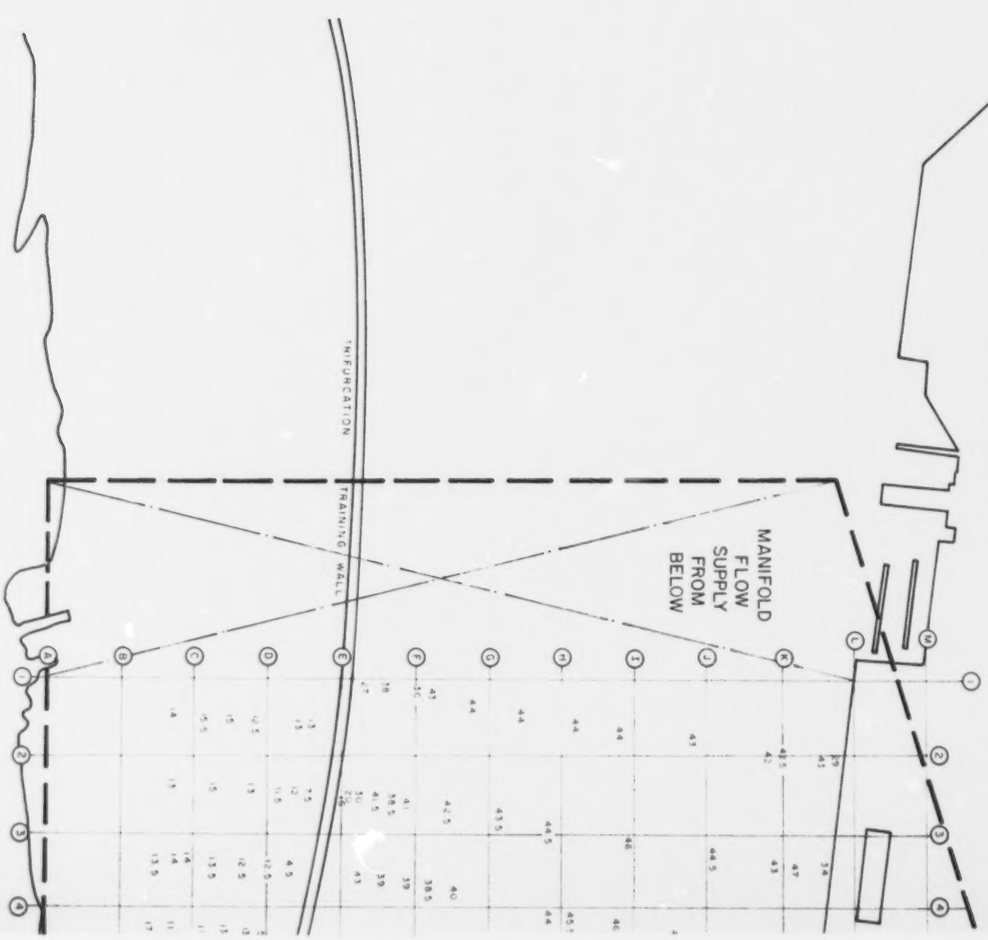


Photo 10 Experiment Control Equipment

FIG.1 LOCATION MAP

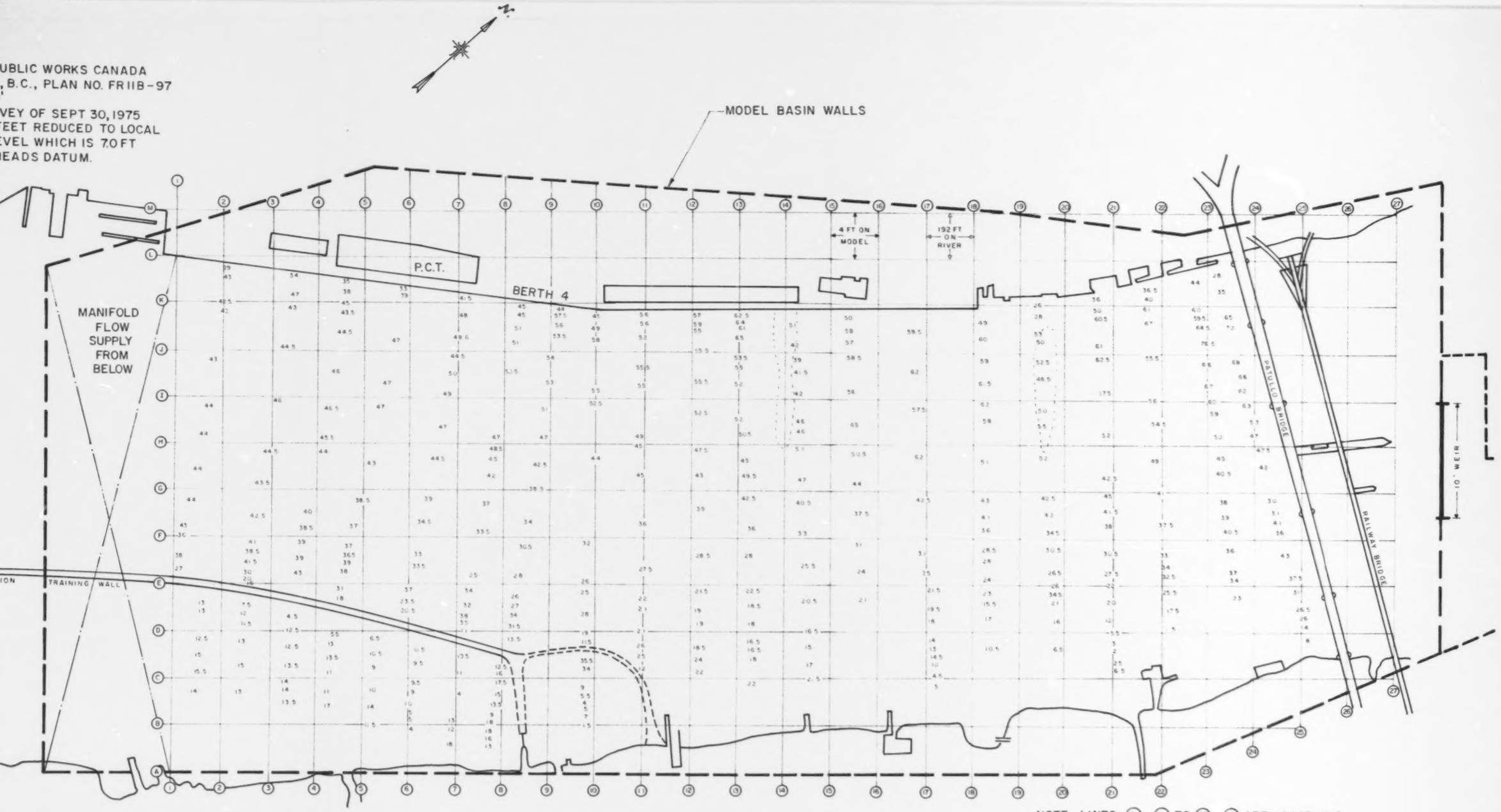


DRAWING REFERENCE PUBLIC WORKS CANADA
FRASER RIVER, B.C., PLAN NO. FR IIB-97
SCALE 1" = 200'
SOUNDING SURVEY OF SEPT 30, 1975
SOUNDING IN FEET REDUCED TO LOCAL
LOW WATER LEVEL WHICH IS 7.0 FT
ABOVE SAND HEADS DATUM.

FIG.2 NE

UBLIC WORKS CANADA
; B.C., PLAN NO. FRIIB-97

VEY OF SEPT 30, 1975
FEET REDUCED TO LOCAL
EVEL WHICH IS 7.0 FT
EADS DATUM.



NOTE LINES ①-① TO ㉗-㉗ ARE LOCATIONS OF TEMPLATES FOR MOULDING OF MODEL RIVER BED

FIG.2 NEW WESTMINSTER SECTION OF FRASER RIVER AS MODELLED TO 1:48 SCALE

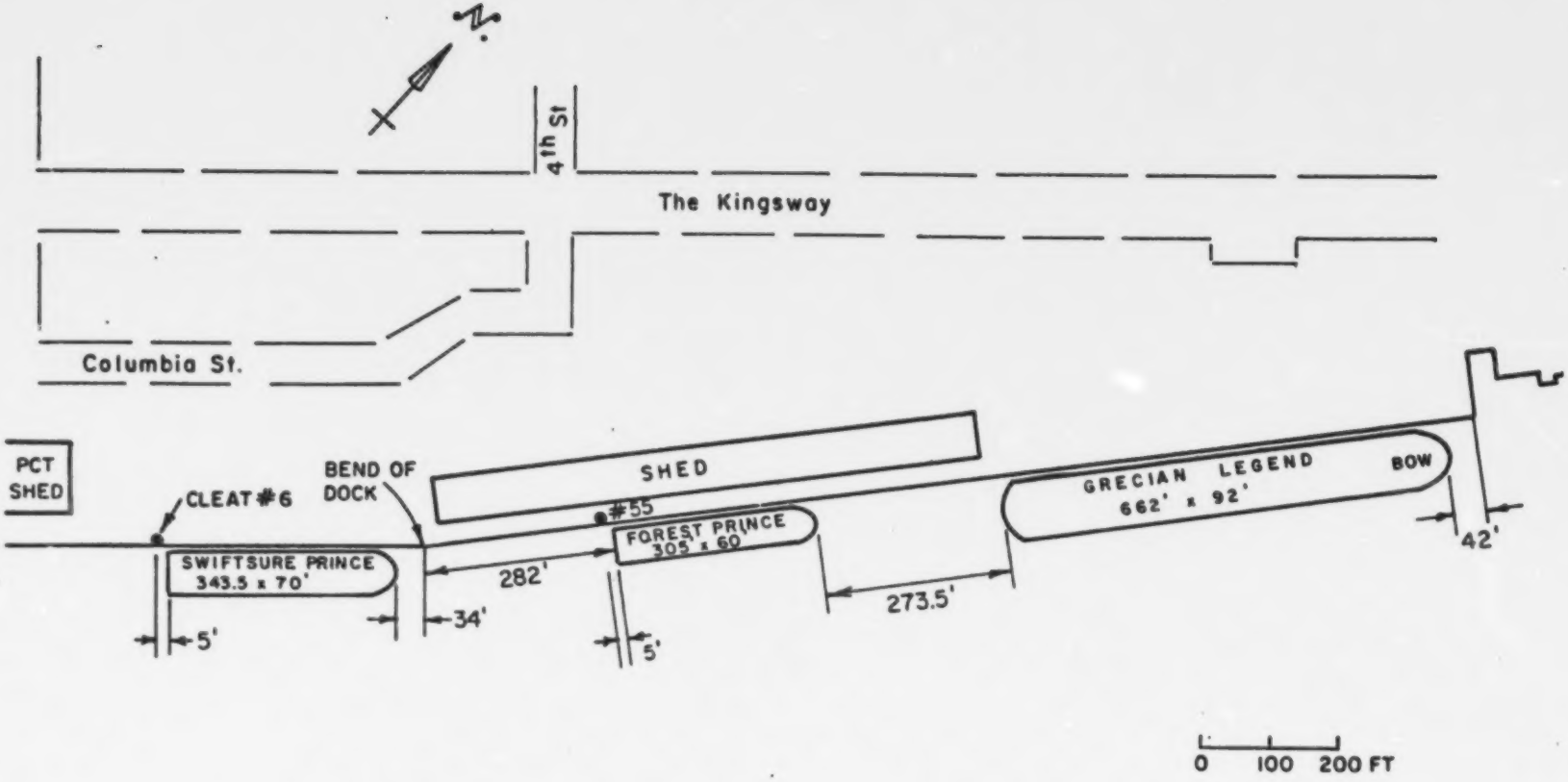
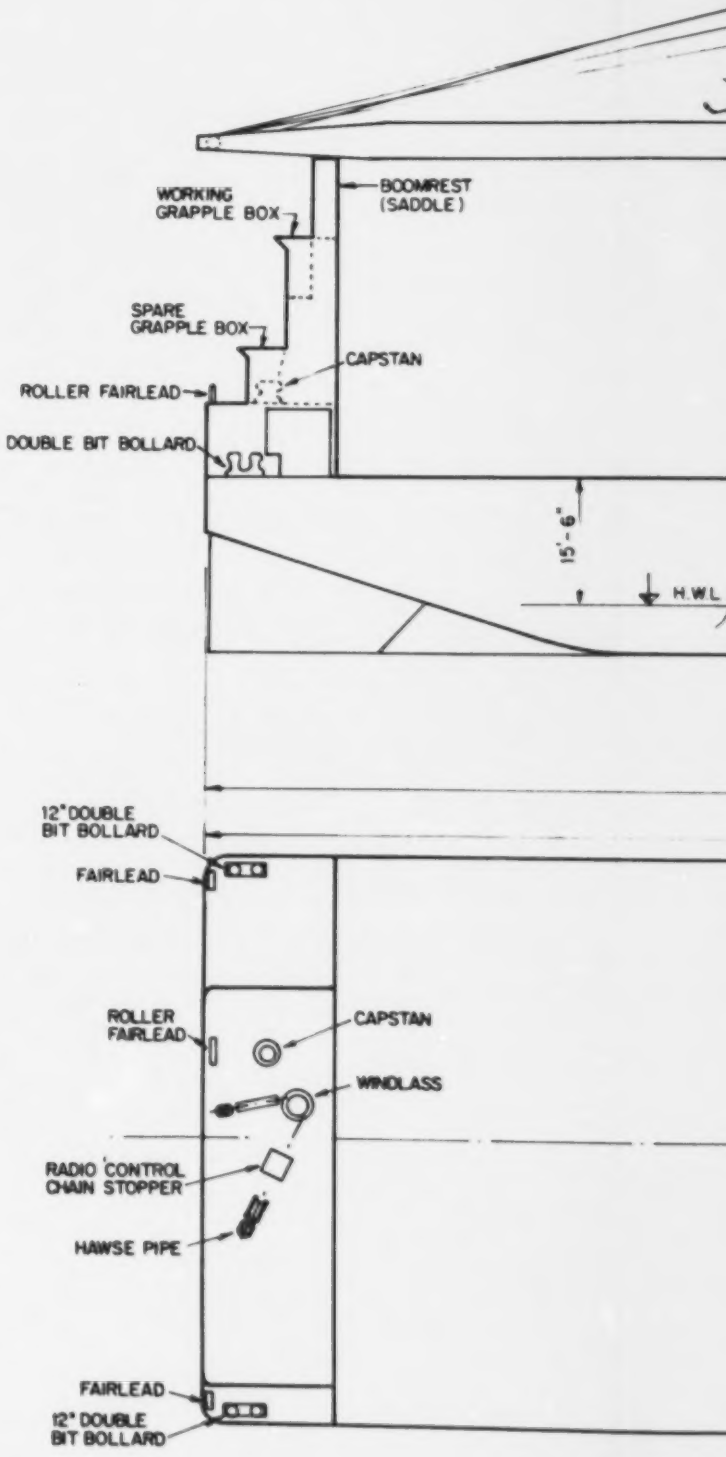
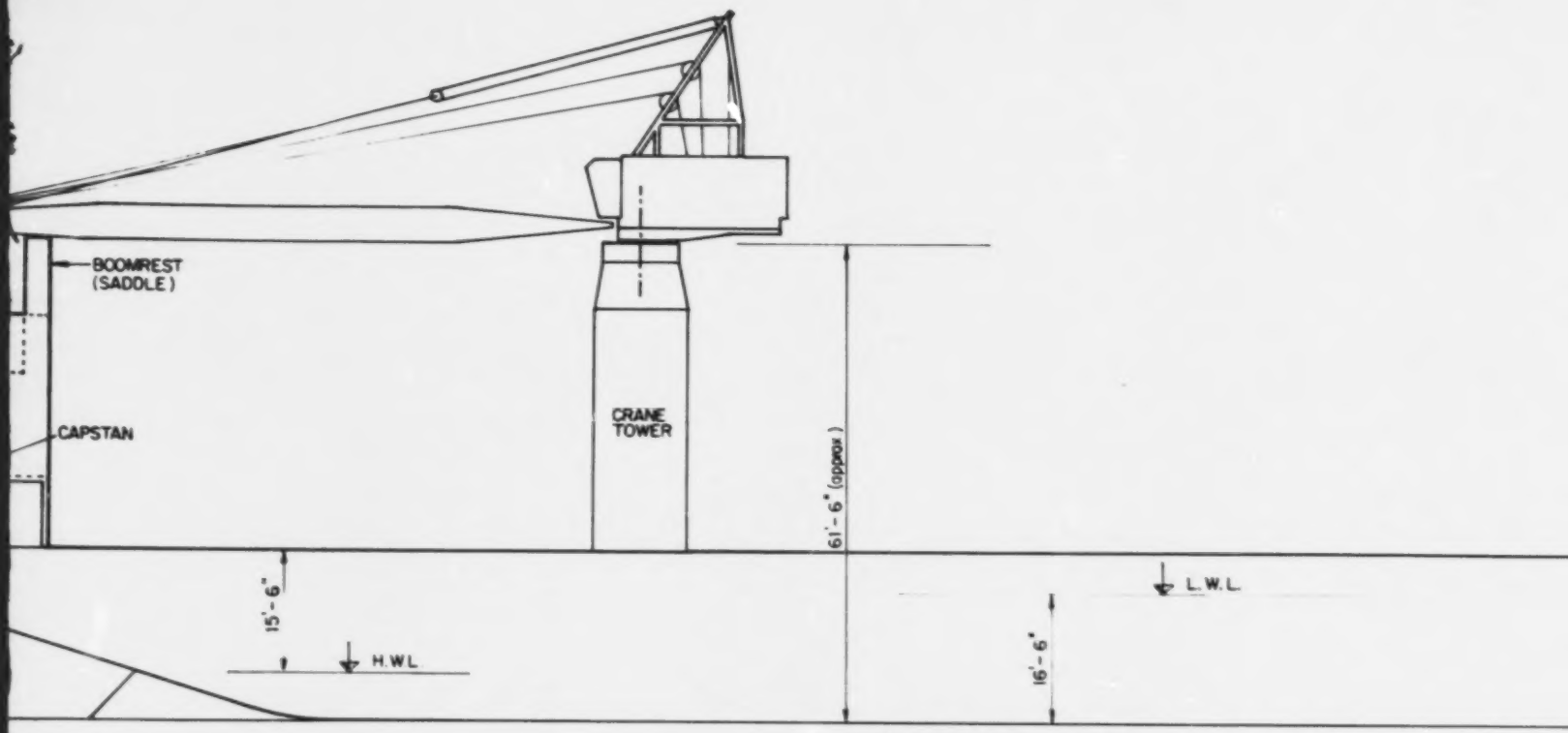
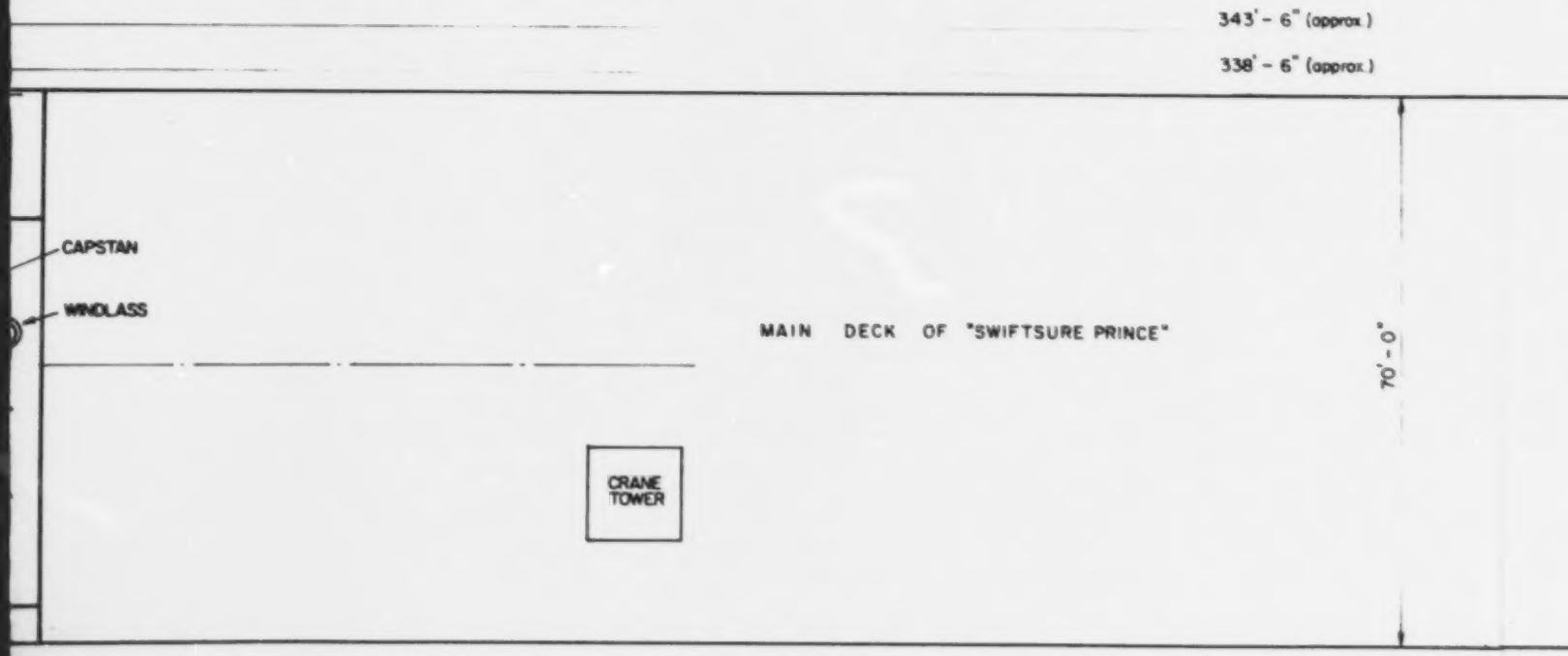


FIG.3 ASSUMED POSITIONS OF SWIFTSURE PRINCE, FOREST PRINCE, AND GRECIAN LEGEND ON DEC. 26, 1975

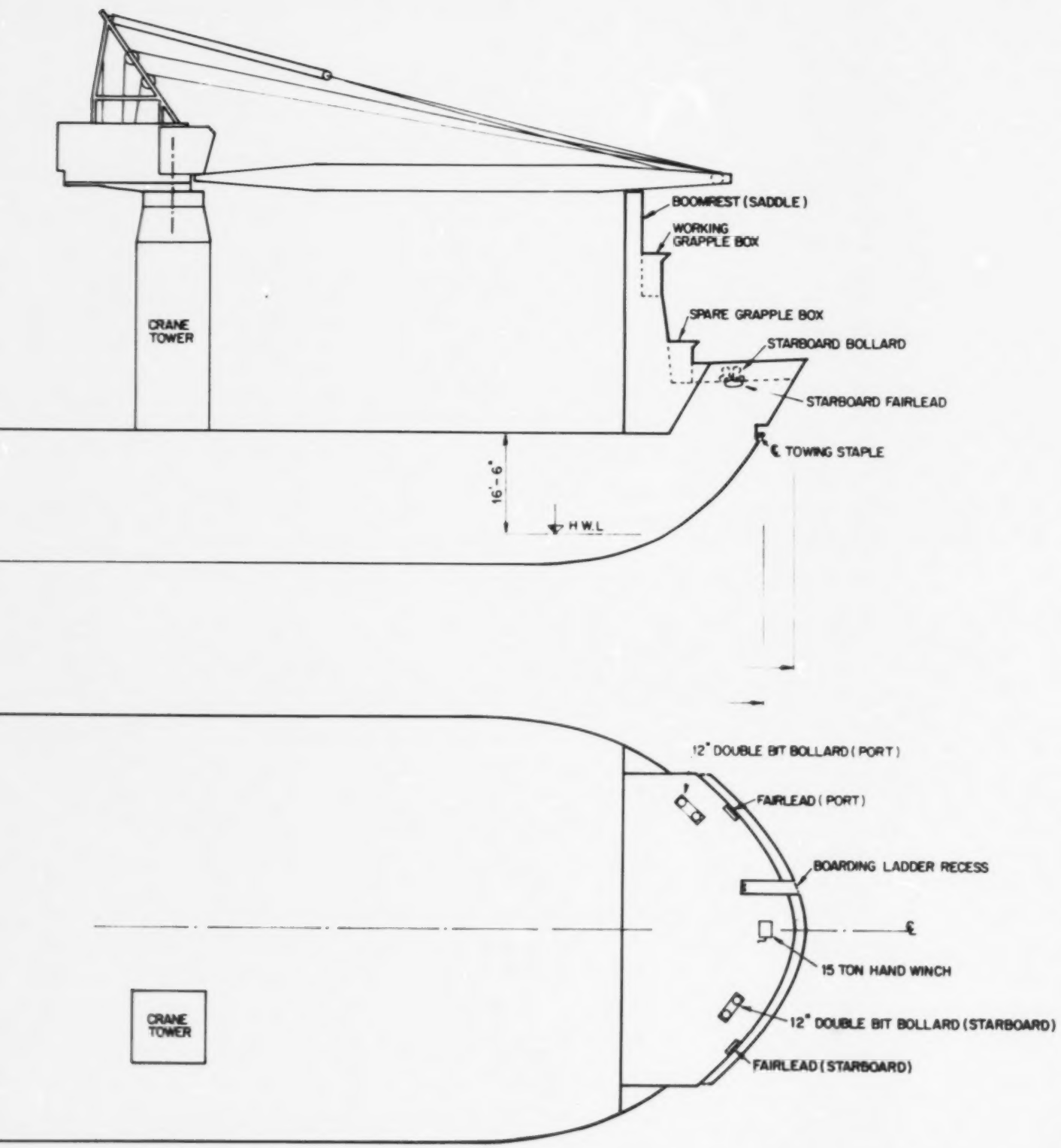

WORKING GRAPPLE BOX
BOOMREST (SADDLE)
SPARE GRAPPLE BOX
CAPSTAN
ROLLER FAIRLEAD
DOUBLE BIT BOLLARD
15'-6"
H.W.L
12" DOUBLE BIT BOLLARD
FAIRLEAD
ROLLER FAIRLEAD
CAPSTAN
WINDLASS
RADIO CONTROL CHAIN STOPPER
HAWSE PIPE
FAIRLEAD
12" DOUBLE BIT BOLLARD

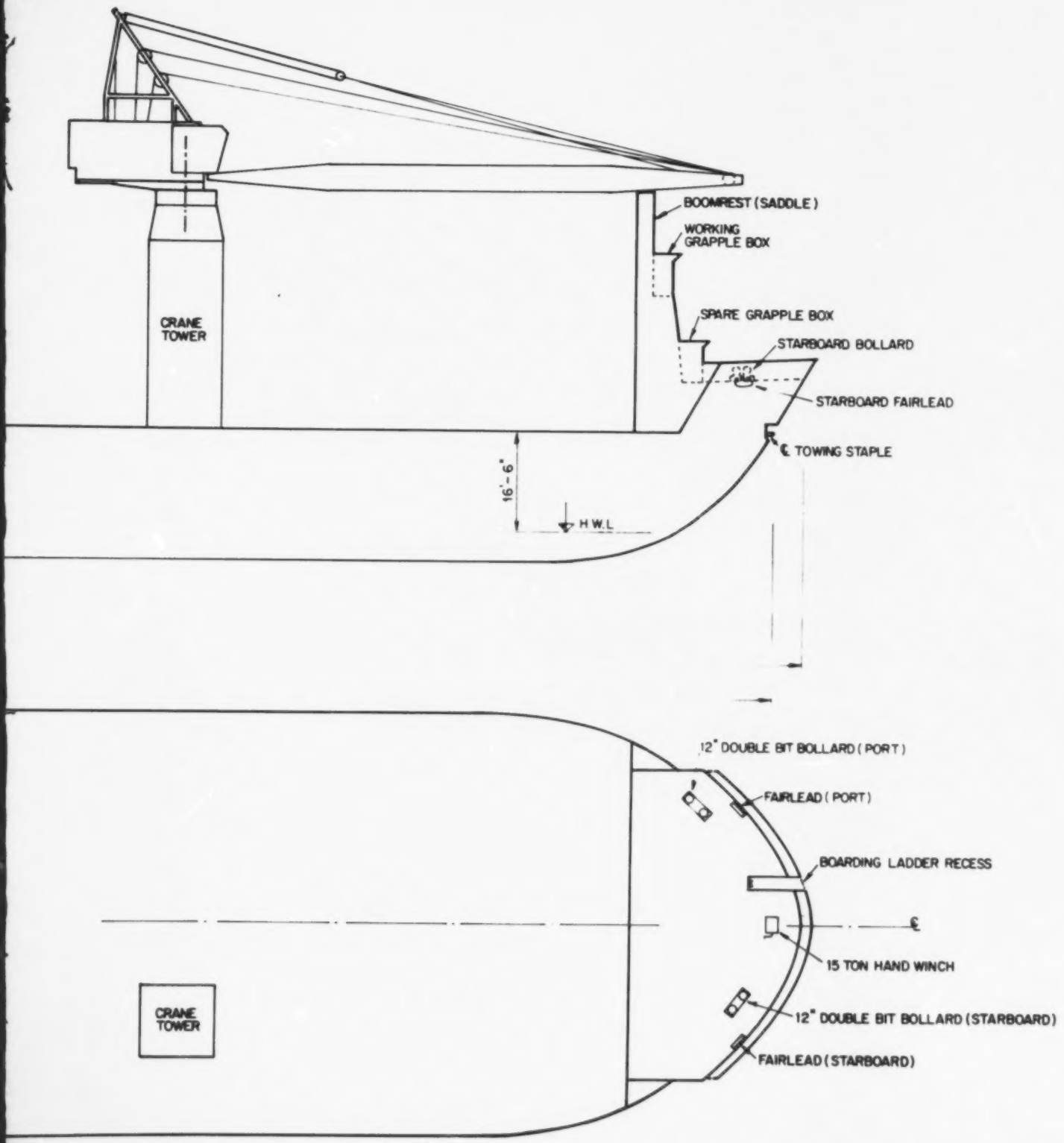


STARBOARD SIDE ELEVATION



PLAN


BOOMREST (SADDLE)
WORKING GRAPPLE BOX
SPARE GRAPPLE BOX
STARBOARD BOLLARD
STARBOARD FAIRLEAD
℄ TOWING STAPLE
CRANE TOWER
16'-6"
H.W.L
12" DOUBLE BIT BOLLARD (PORT)
FAIRLEAD (PORT)
BOARDING LADDER RECESS
℄
15 TON HAND WINCH
12" DOUBLE BIT BOLLARD (STARBOARD)
FAIRLEAD (STARBOARD)
CRANE TOWER


BOOMREST (SADDLE)
WORKING GRAPPLE BOX
SPARE GRAPPLE BOX
STARBOARD BOLLARD
STARBOARD FAIRLEAD
℄ TOWING STAPLE
CRANE TOWER
16'-6"
H.W.L
12" DOUBLE BIT BOLLARD (PORT)
FAIRLEAD (PORT)
BOARDING LADDER RECESS
℄
15 TON HAND WINCH
12" DOUBLE BIT BOLLARD (STARBOARD)
FAIRLEAD (STARBOARD)
CRANE TOWER

Public Works Canada / Travaux publics Canada

FIGURE. 4

project / projet

FRASER RIVER RAILWAY BRIDGE AT NEW WESTMINSTER, B.C.

THE SHIP SWIFTSURE PRINCE

drawing / dessin

GENERAL OUTLINE AND MAJOR DIMENSIONS

scale 1" = 20'

designed H. I. LANGLEY / conçu

date JULY 1980

drawn I.F. / dessiné

date JULY 1980

reviewed H. I. LANGLEY / examiné

date H. I. Langley 1980-07-03

approved D. P. DODGE / approuvé

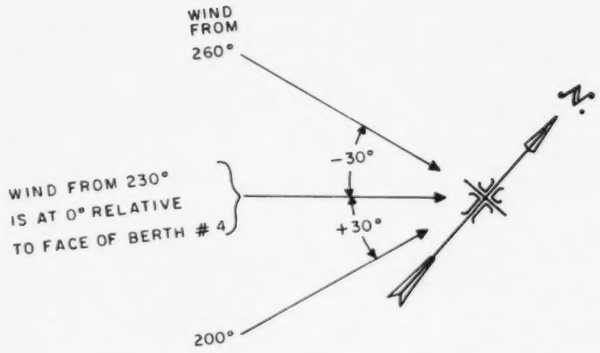
date 1980-07-03

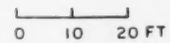
Tender / Soumission

PWC Project Manager / Administrateur de projets TPC

project number / no. du projet

drawing no. / no. du dessin





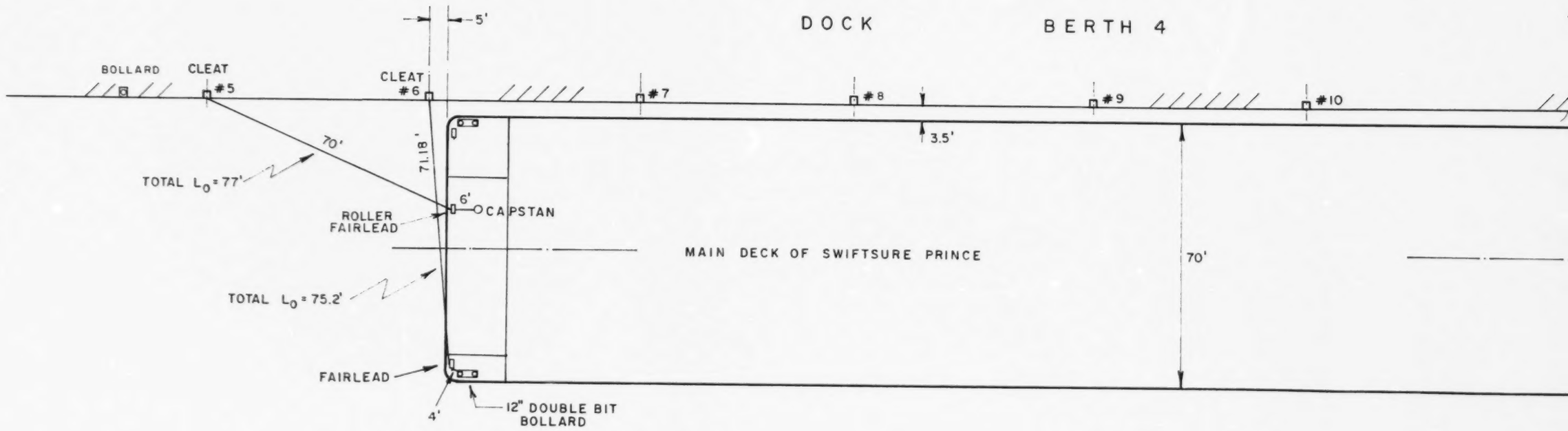
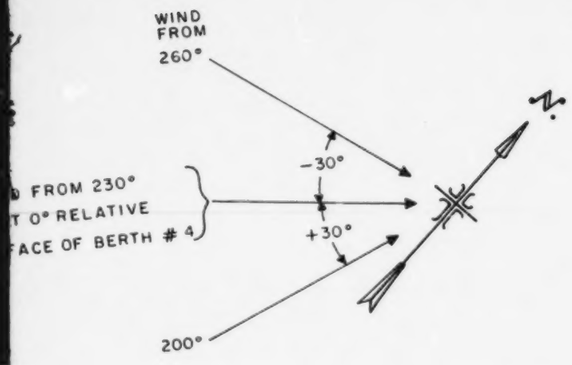
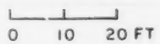
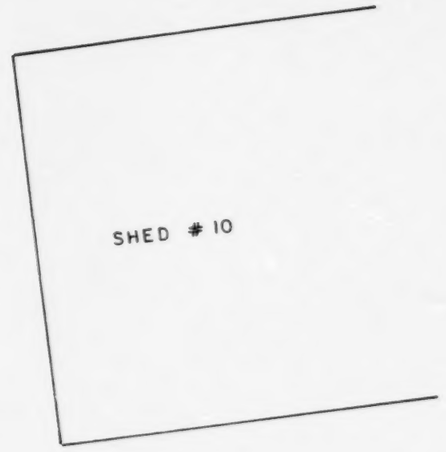


FIG.5a ASSUMED POSITION OF SWIFTSURE PRINCE AS TIE
DEC 20, 1975 , 0415 HRS, TIDE AT 6.75 FT (SAND HEADS DA

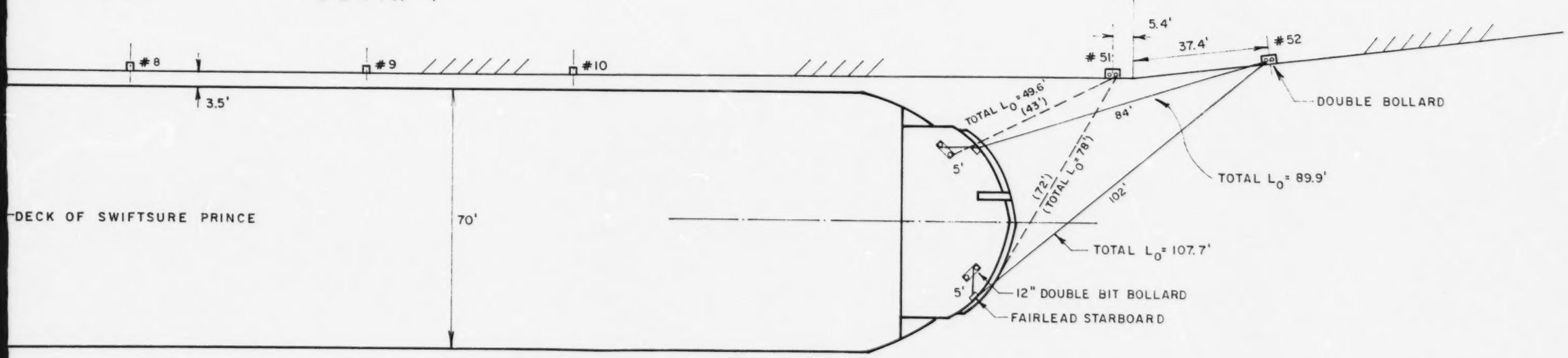
LINE LENGTHS SHOWN ARE HORIZONTAL PROJECTION LENGTHS ONLY
ACTUAL TAUT LENGTHS INCLUDING ON-BOARD LENGTH ARE 'L_0'







DOCK BERTH 4



SUMED POSITION OF SWIFTSURE PRINCE AS TIED UP
75 , 0415 HRS, TIDE AT 6.75 FT (SAND HEADS DATUM)

HOWN ARE HORIZONTAL PROJECTION LENGTHS ONLY
NGTHS INCLUDING ON-BOARD LENGTH ARE 'L_0'

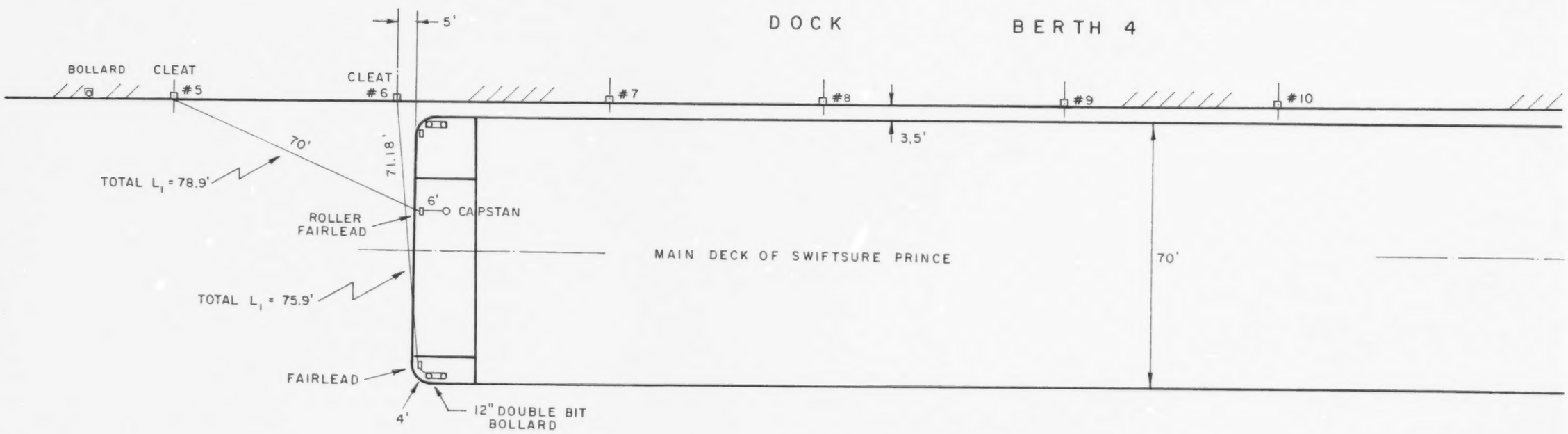
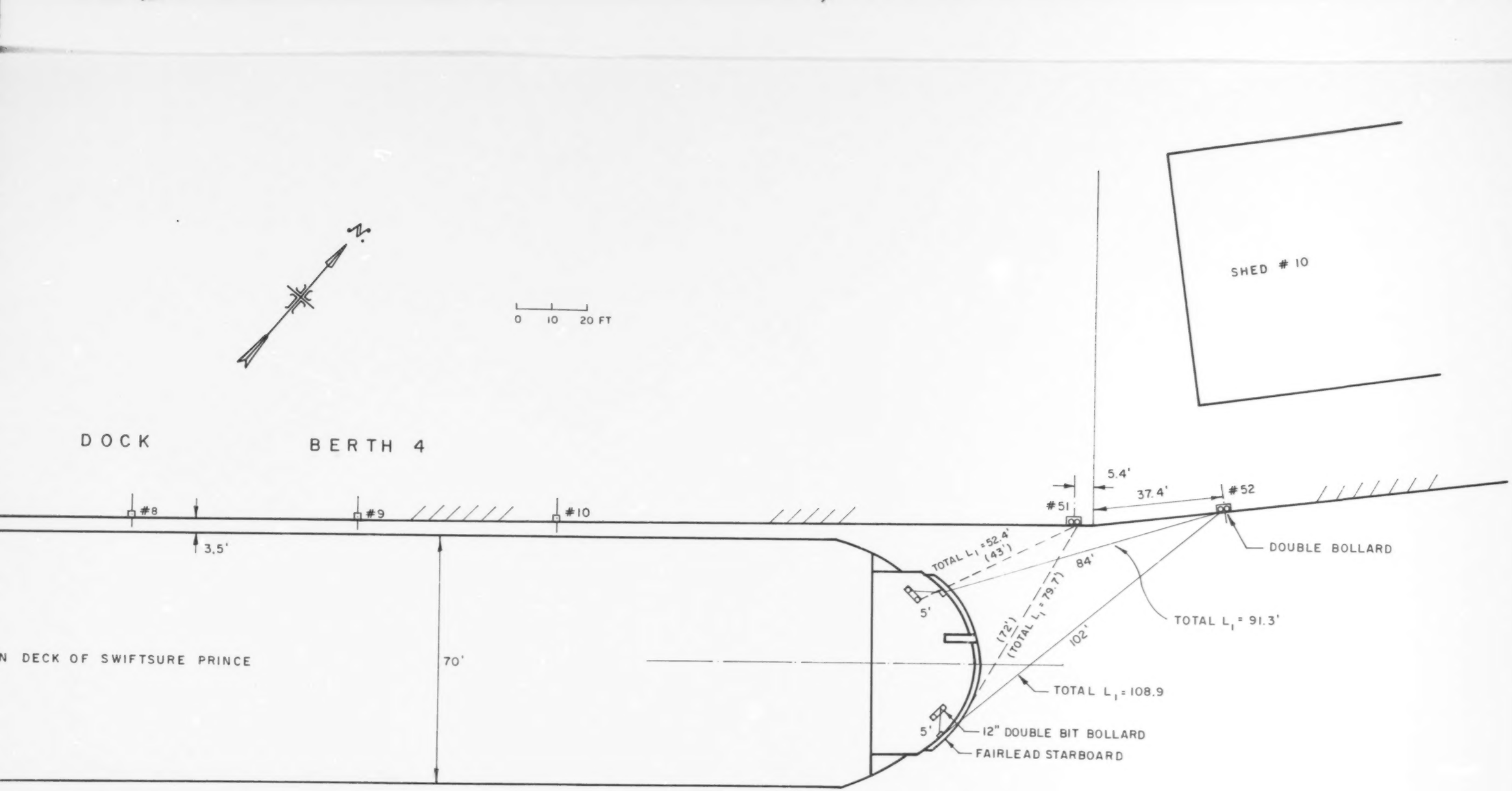


FIG.5b ASSUMED POSITION OF SWIFTSURE PRINCE JUST BEFORE ... DEC 26, 1975, 1400 HRS, TIDE AT 14.68 FT (SAND HEADS DATUM), FRO...

LINE LENGTHS SHOWN ARE HORIZONTAL PROJECTION LENGTHS ONLY
ACTUAL TAUT LENGTHS INCLUDING ON-BOARD LENGTH ARE 'L_1'

DOCK

BERTH 4



POSITION OF SWIFTSURE PRINCE JUST BEFORE ACCIDENT
S, TIDE AT 14.68FT (SAND HEADS DATUM), FROM APPENDIX I

LENGTHS SHOWN ARE HORIZONTAL PROJECTION LENGTHS ONLY
AL TAUT LENGTHS INCLUDING ON-BOARD LENGTH ARE 'L_1'

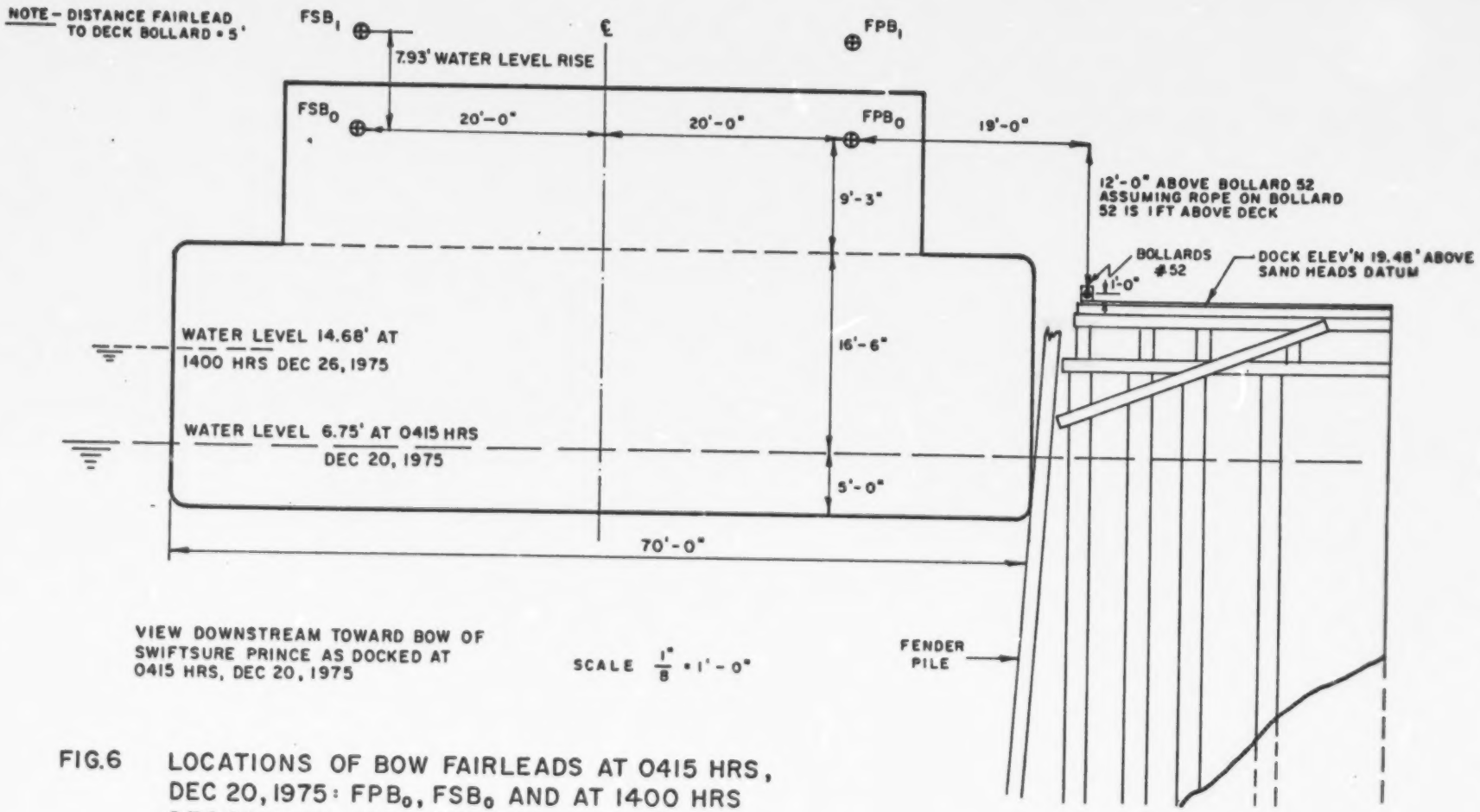


FIG.6 LOCATIONS OF BOW FAIRLEADS AT 0415 HRS, DEC 20, 1975: FPB_0, FSB_0 AND AT 1400 HRS DEC 26, 1975: FPB_1, FSB_1.

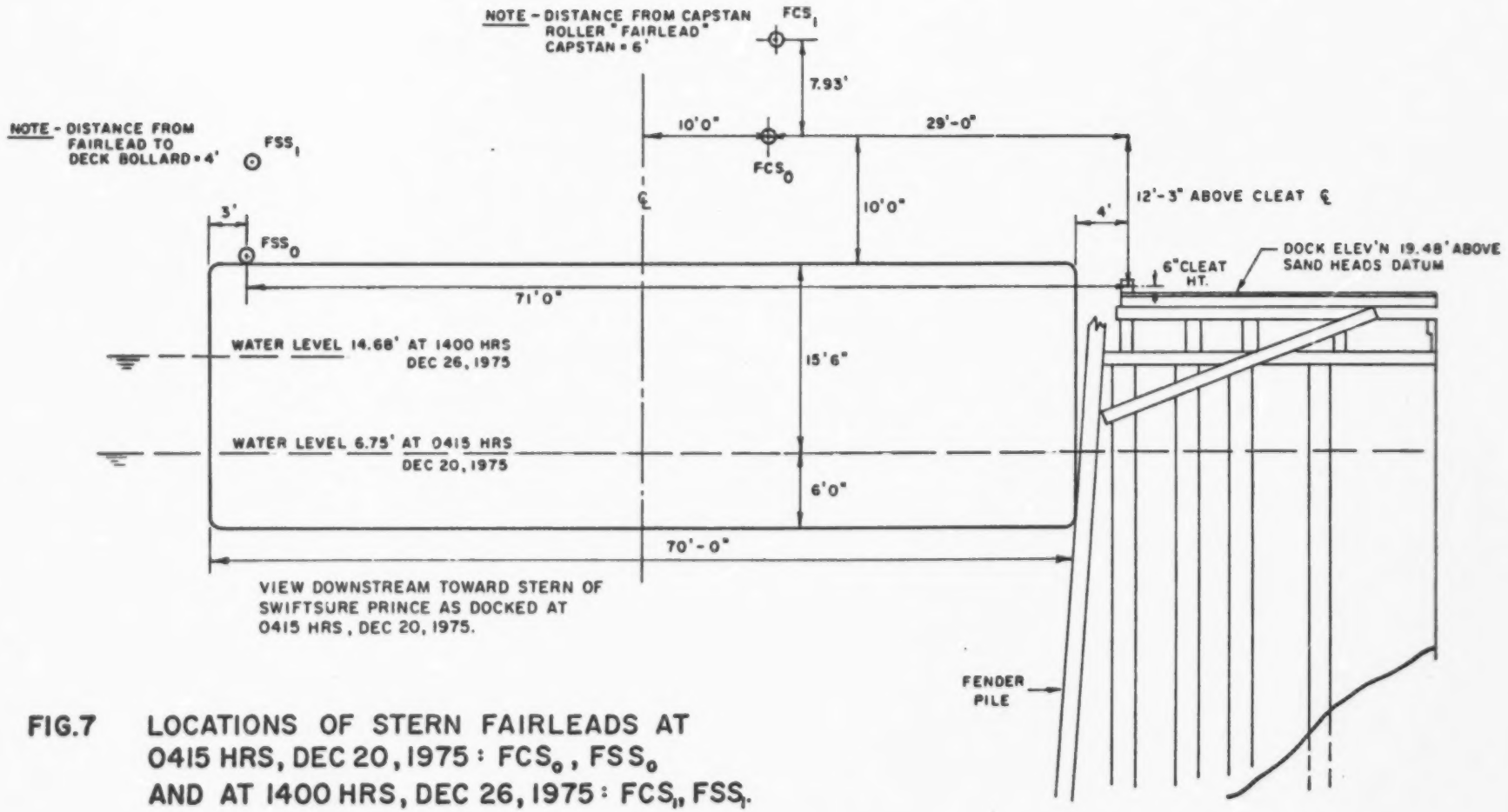
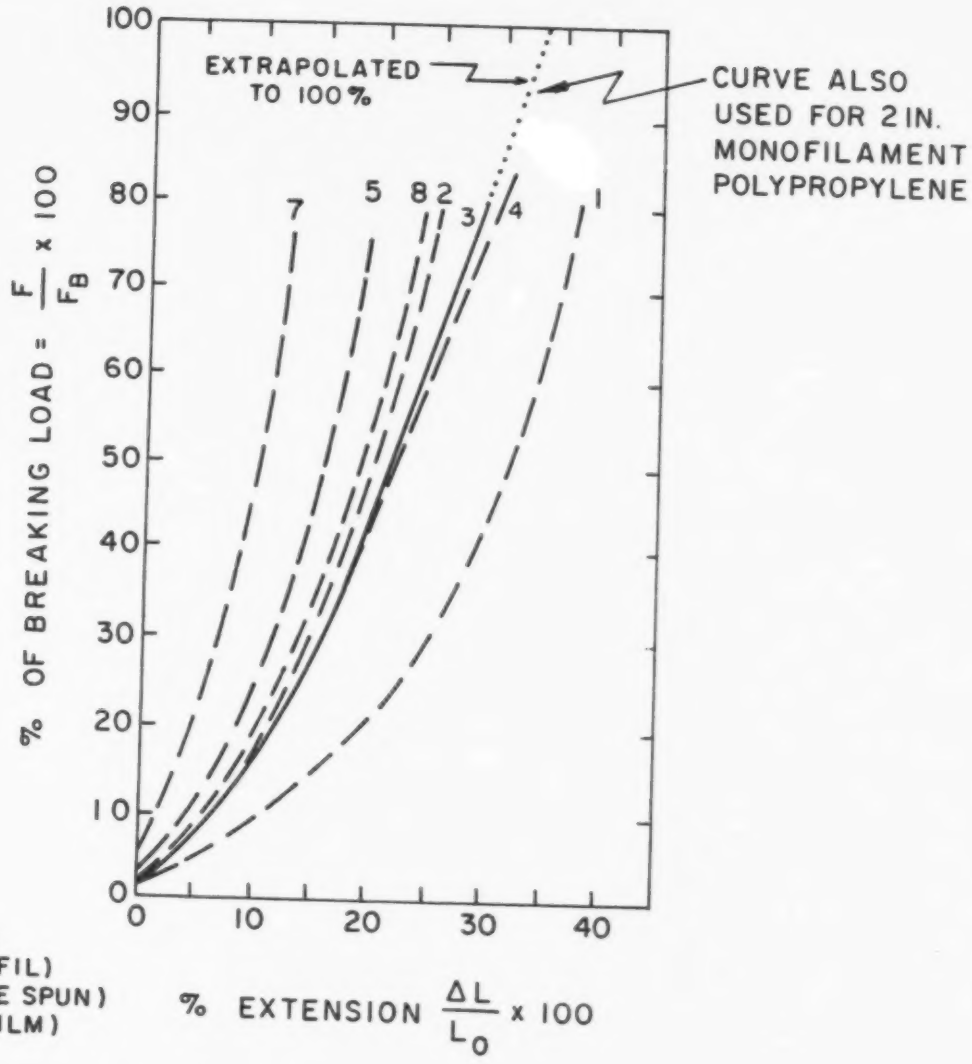


FIG.7 LOCATIONS OF STERN FAIRLEADS AT 0415 HRS, DEC 20, 1975 : FCS_0, FSS_0 AND AT 1400 HRS, DEC 26, 1975 : FCS_1, FSS_1.

SOURCE: REF. 26, BSRA, REPORT NS179, 1967, FIG. 27



CURVE MAT'L
1. NYLON 266
2. TERYLENE TYPE H
3. POLY PROP (MULTIFIL)
4. POLY PROP (STAPLE SPUN)
5. POLY PROP (SLIT FILM)
6. POLYETHYLENE
7. MANILA
8. PERLON

FIG. 8 % BREAKING LOAD VS % EXTENSION FOR "NEW OR "LIGHTLY-USED" 6 INCH CIRCUMFERENCE (2 IN. NOM DIA) 3-STRAND ROPES POLYPROP. ROPES

REF.26 BSRA REPT NS179 ,1967

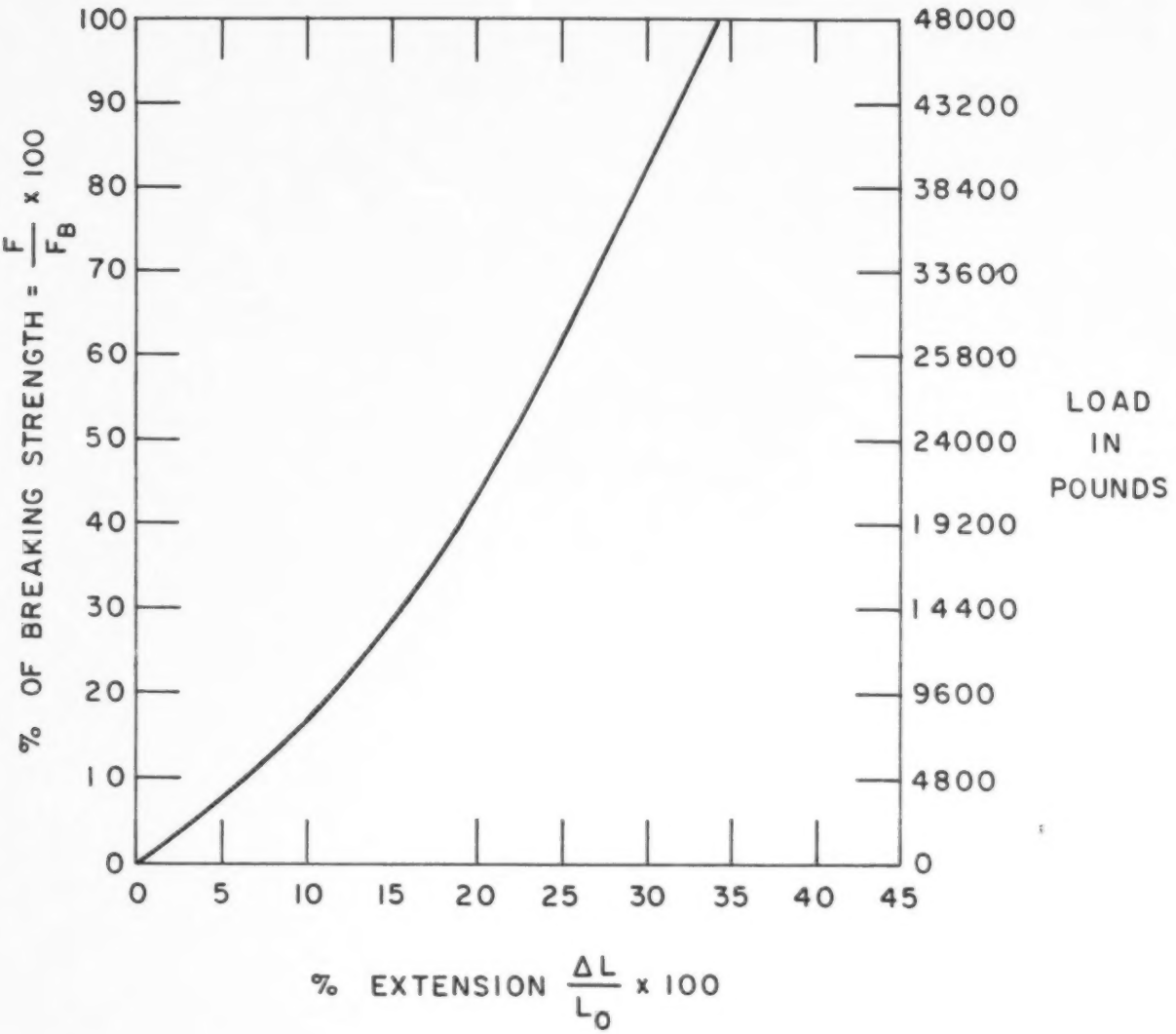


FIG.9 LOAD VS ELONGATION FOR "NEW" OR "LIGHTLY PRE-USED" ROPES, 6" CIRCUMFERENCE, 48mm (2 INCH NOM. DIA) 3-STRAND MONOFILAMENT POLYPROPYLENE ROPES

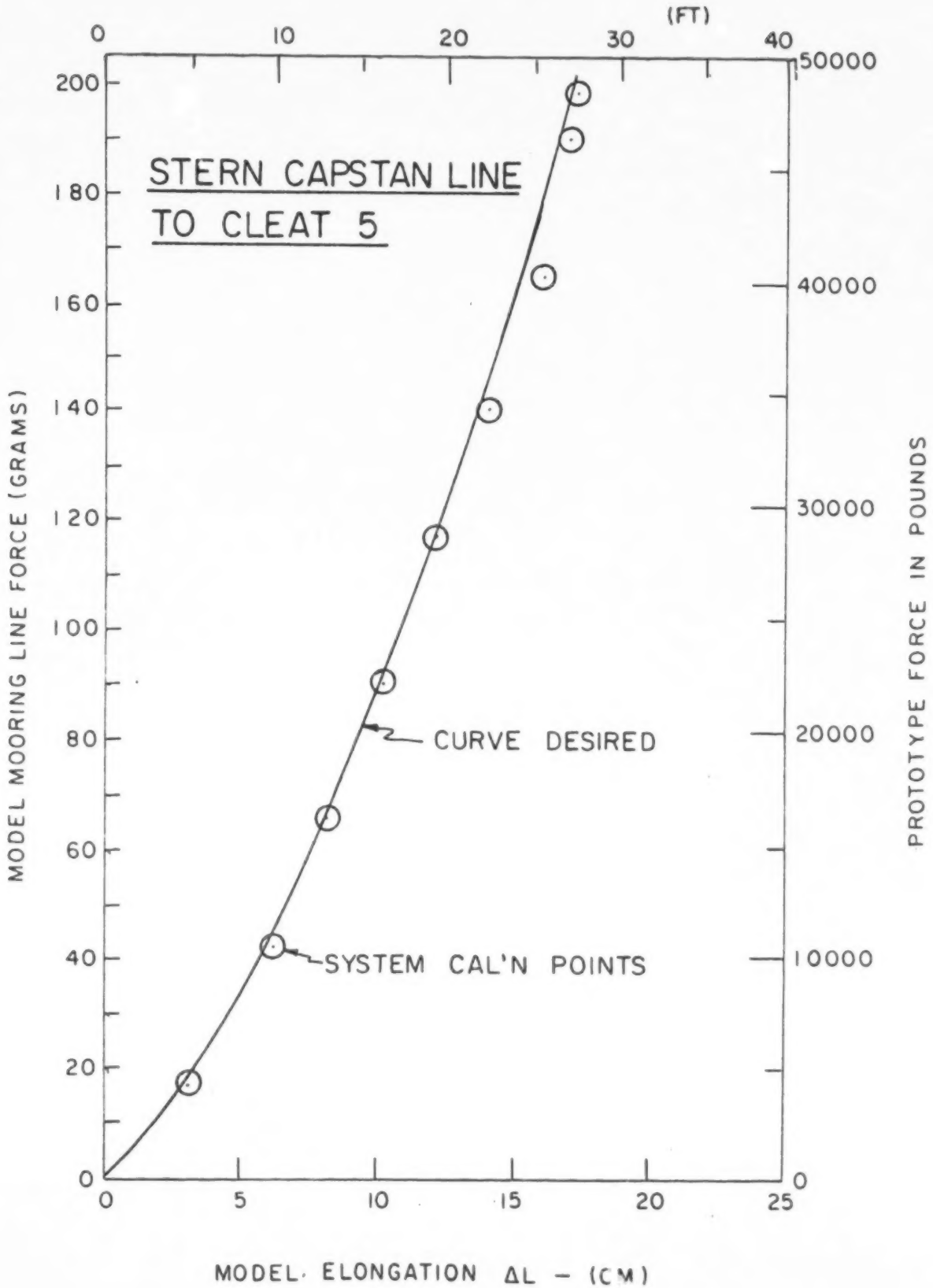


FIG. 10 LOAD-ELONGATION CALIBRATION
"NEW OR LIGHTLY-USED" POLY. LINE

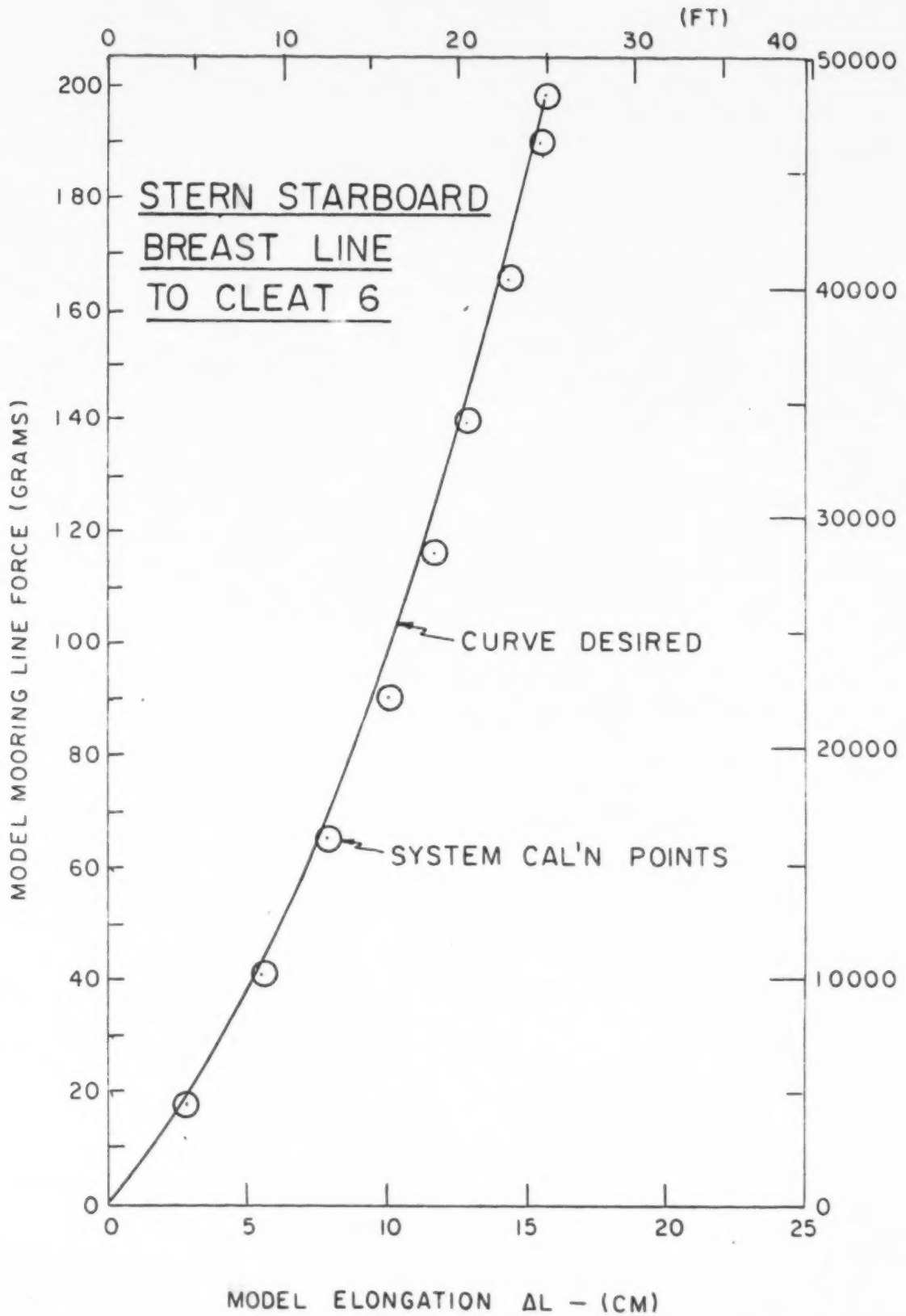


FIG.11 LOAD-ELONGATION CALIBRATION
"NEW OR LIGHTLY-USED" POLY. LINE

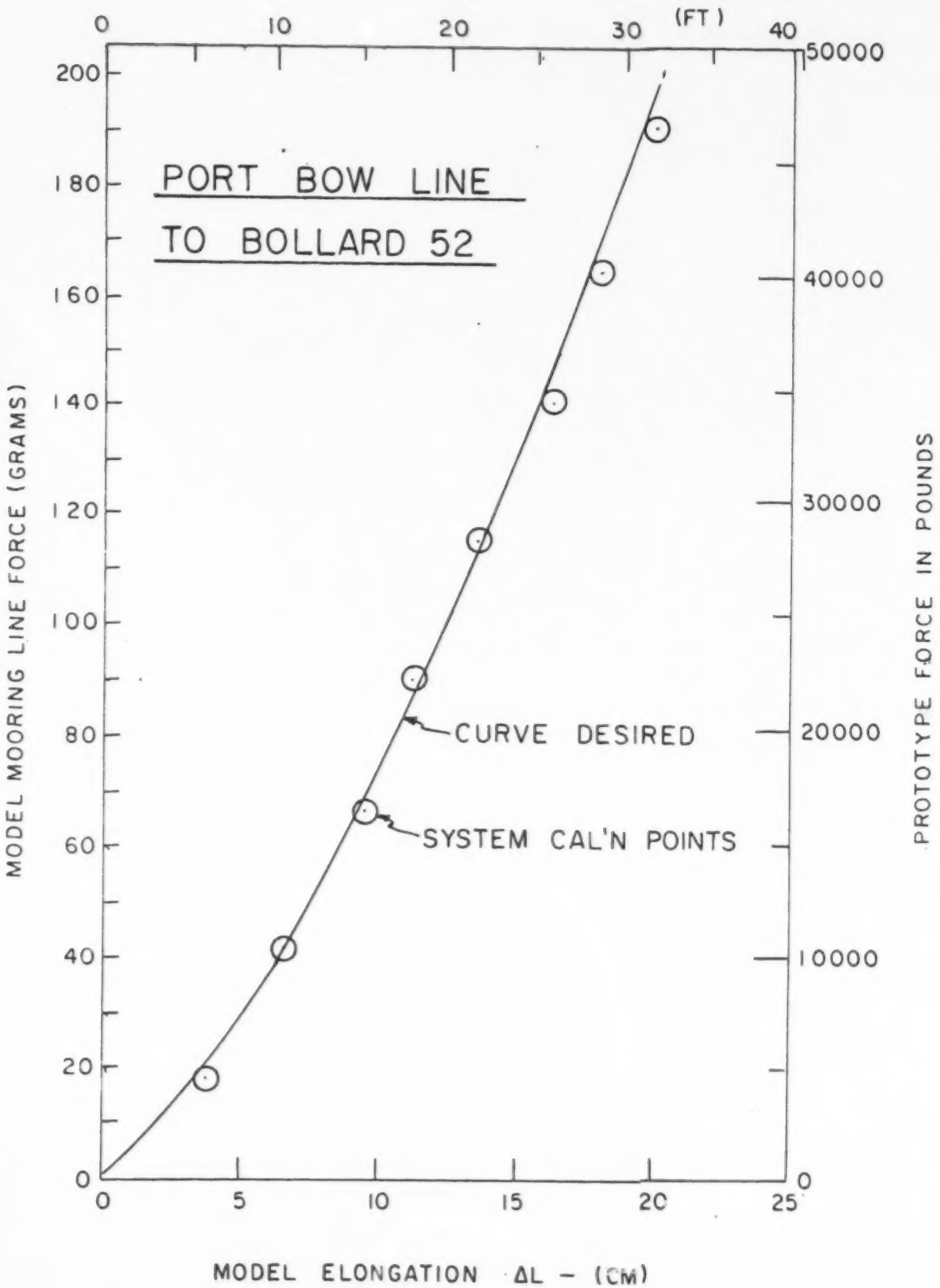


FIG.12 LOAD-ELONGATION CALIBRATION
"NEW OR LIGHTLY-USED" POLY. LINE

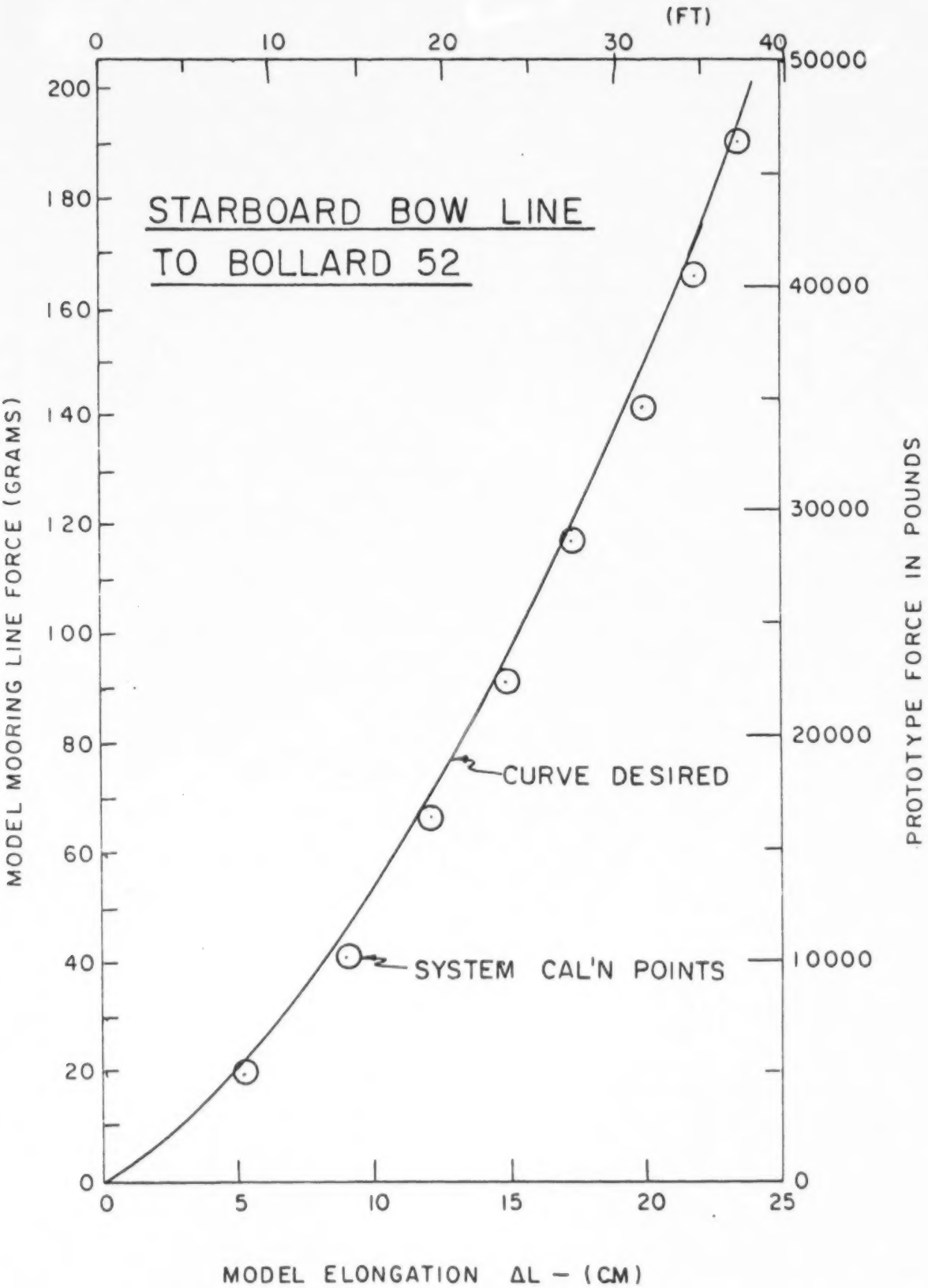


FIG.13 LOAD-ELONGATION CALIBRATION
"NEW OR LIGHTLY-USED" POLY. LINE

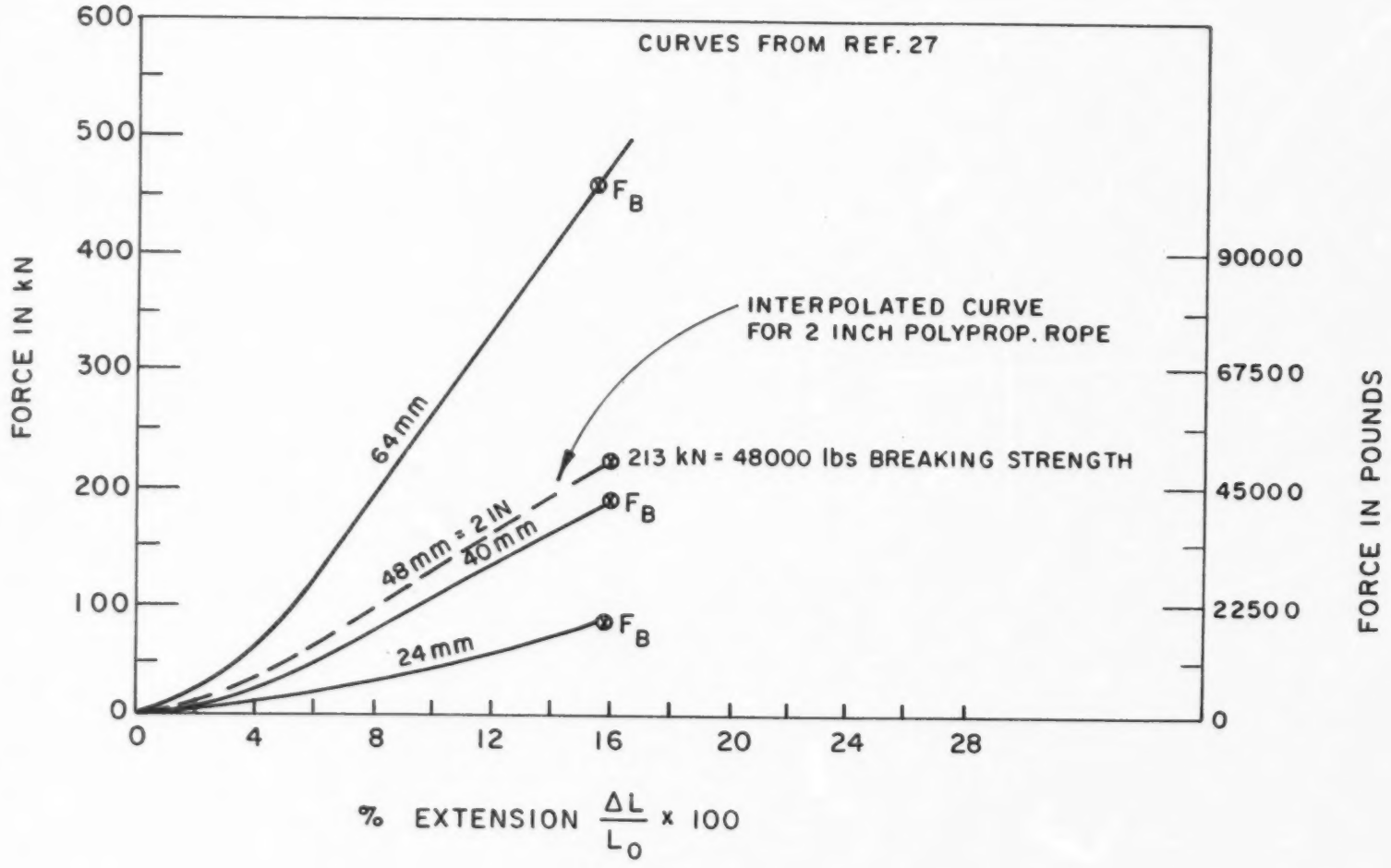


FIG.14 LOAD VERSUS EXTENSION CURVES FOR "SEVERELY USED" POLYPROPYLENE ROPES. (i.e. AFTER 120 LOADINGS TO 50% OF RATED BREAKING STRENGTH)

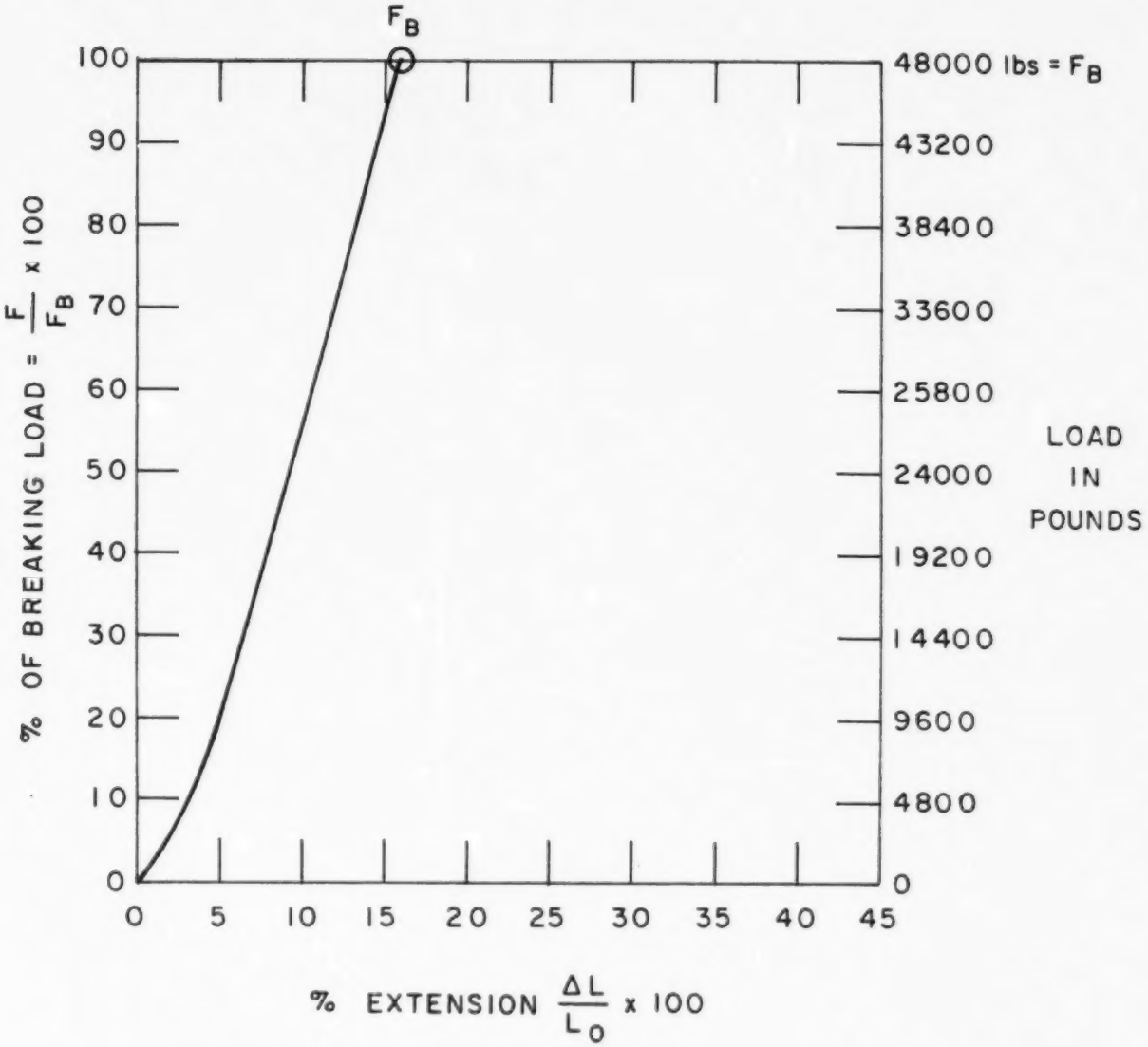


FIG.15 ASSUMED CURVE FROM FIG.14 FOR SEVERELY USED OR PRE-STRETCHED 6" CIRCUMFERENCE MONOFILAMENT POLYPROPYLENE ROPE

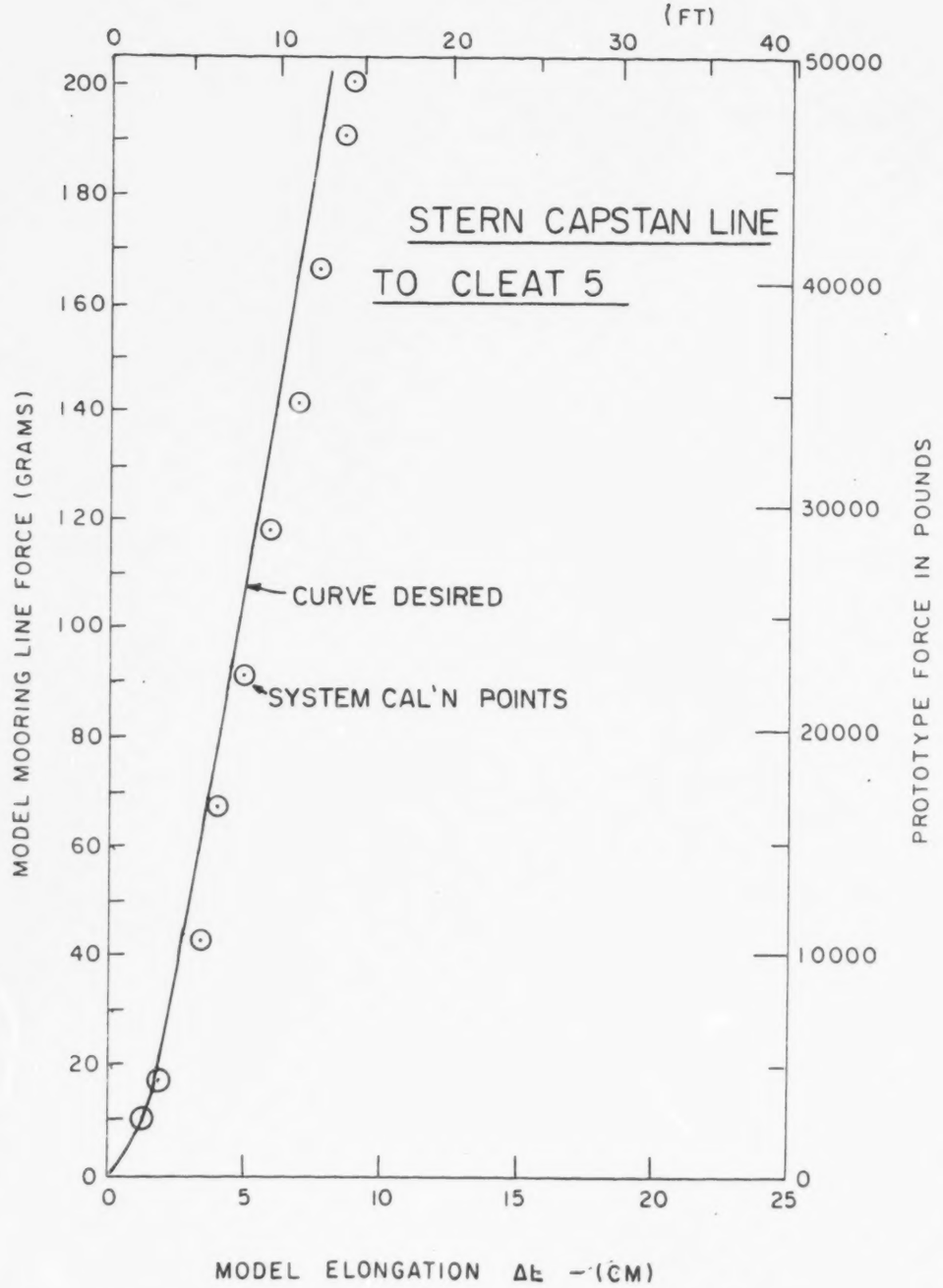


FIG.16 LOAD-ELONGATION CALIBRATION
"SEVERELY-USED" POLY. LINE

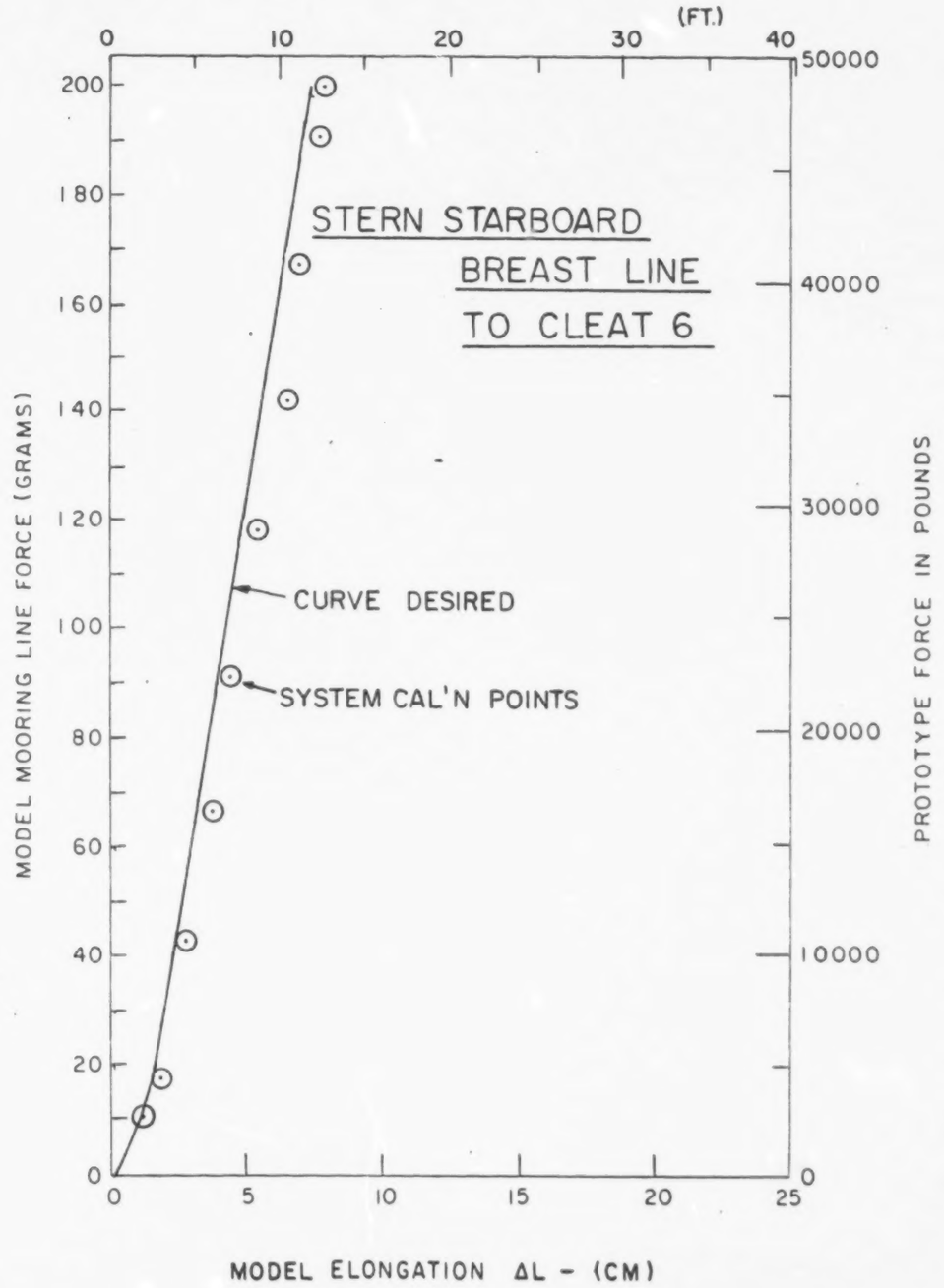


FIG.17 LOAD-ELONGATION CALIBRATION
"SEVERELY-USED" POLY. LINE

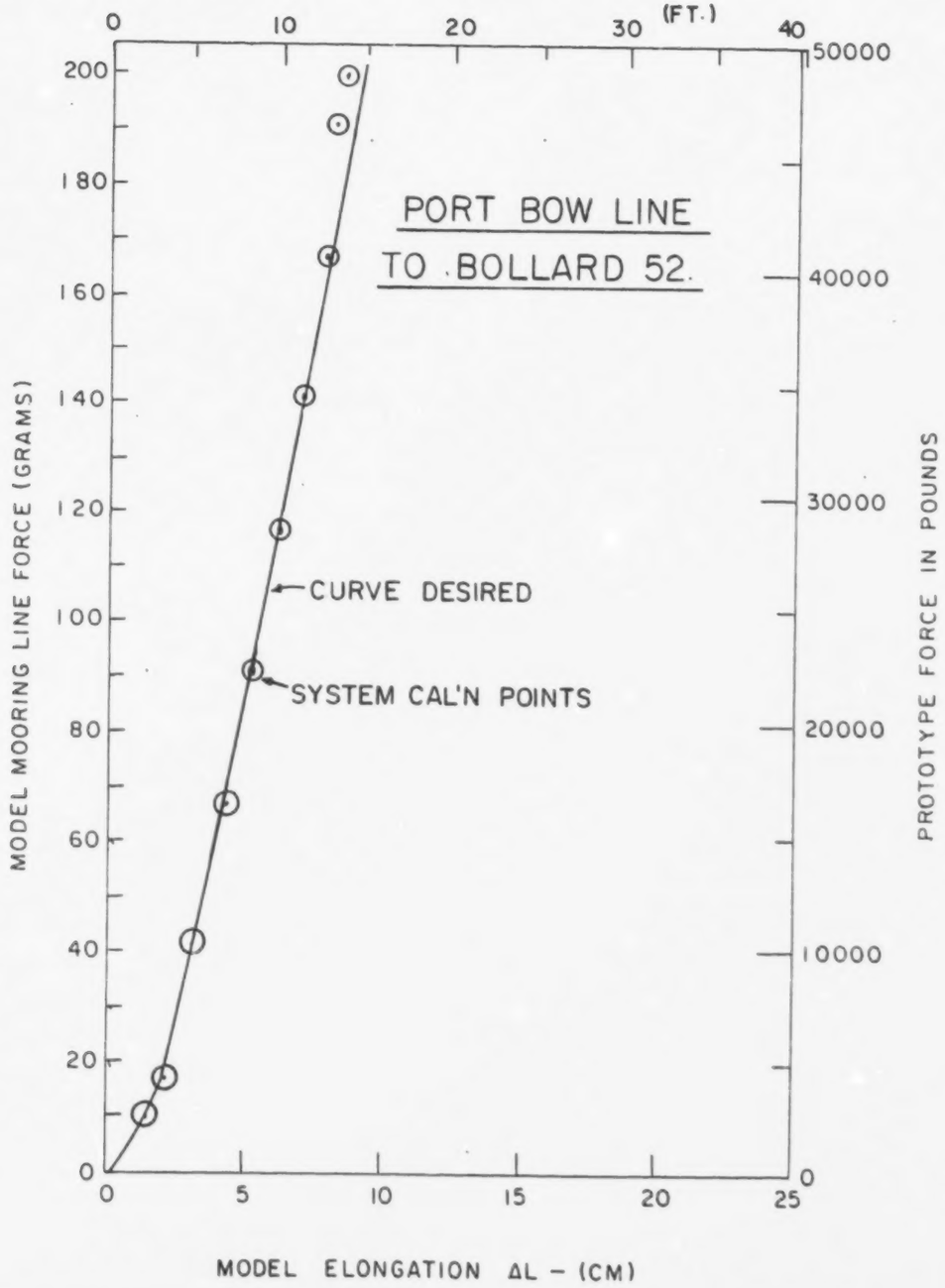


FIG.18 LOAD-ELONGATION CALIBRATION
"SEVERELY-USED" POLY. LINE

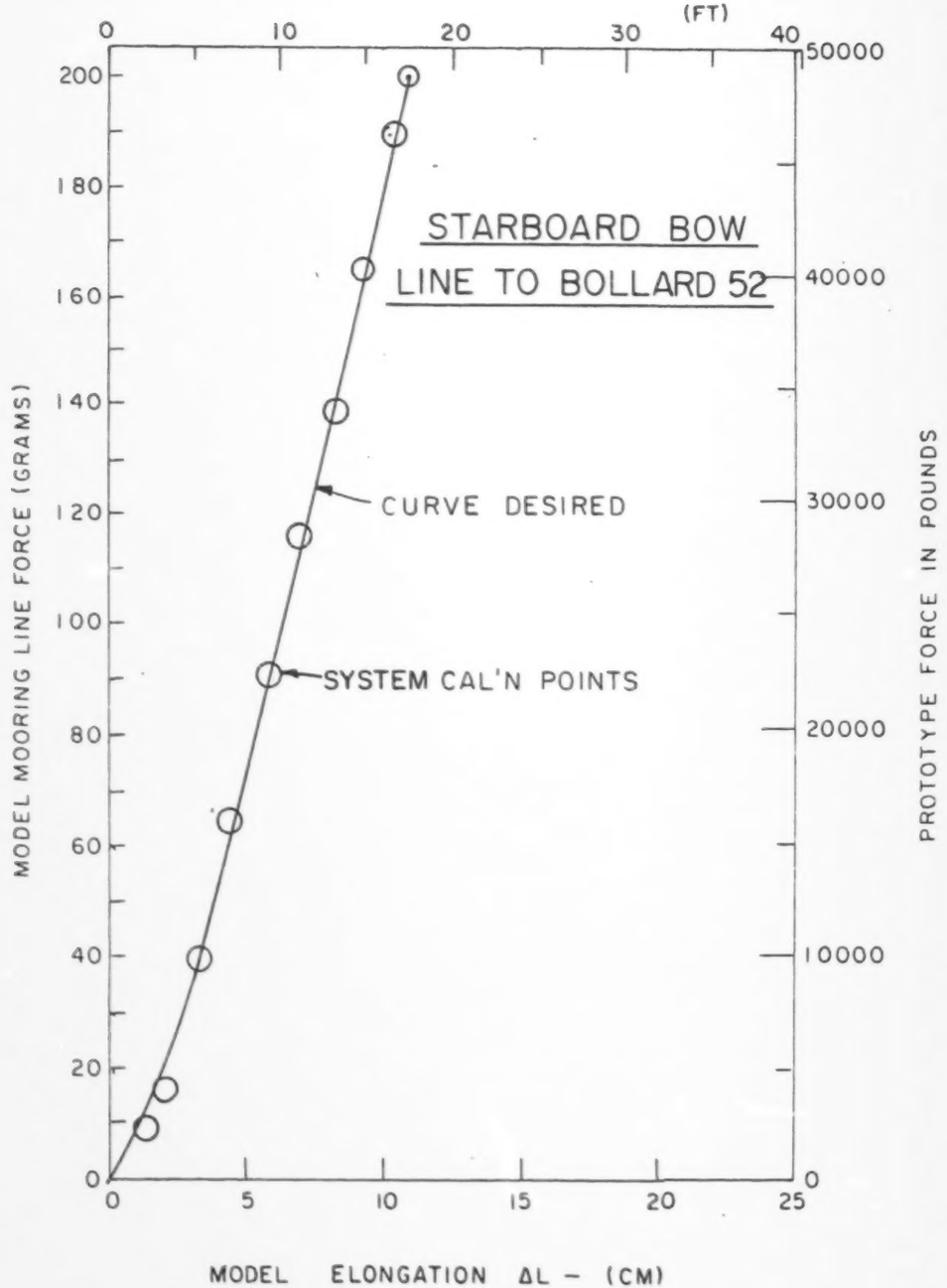


FIG.19 LOAD-ELONGATION CALIBRATION
"SEVERELY-USED" POLY. LINE

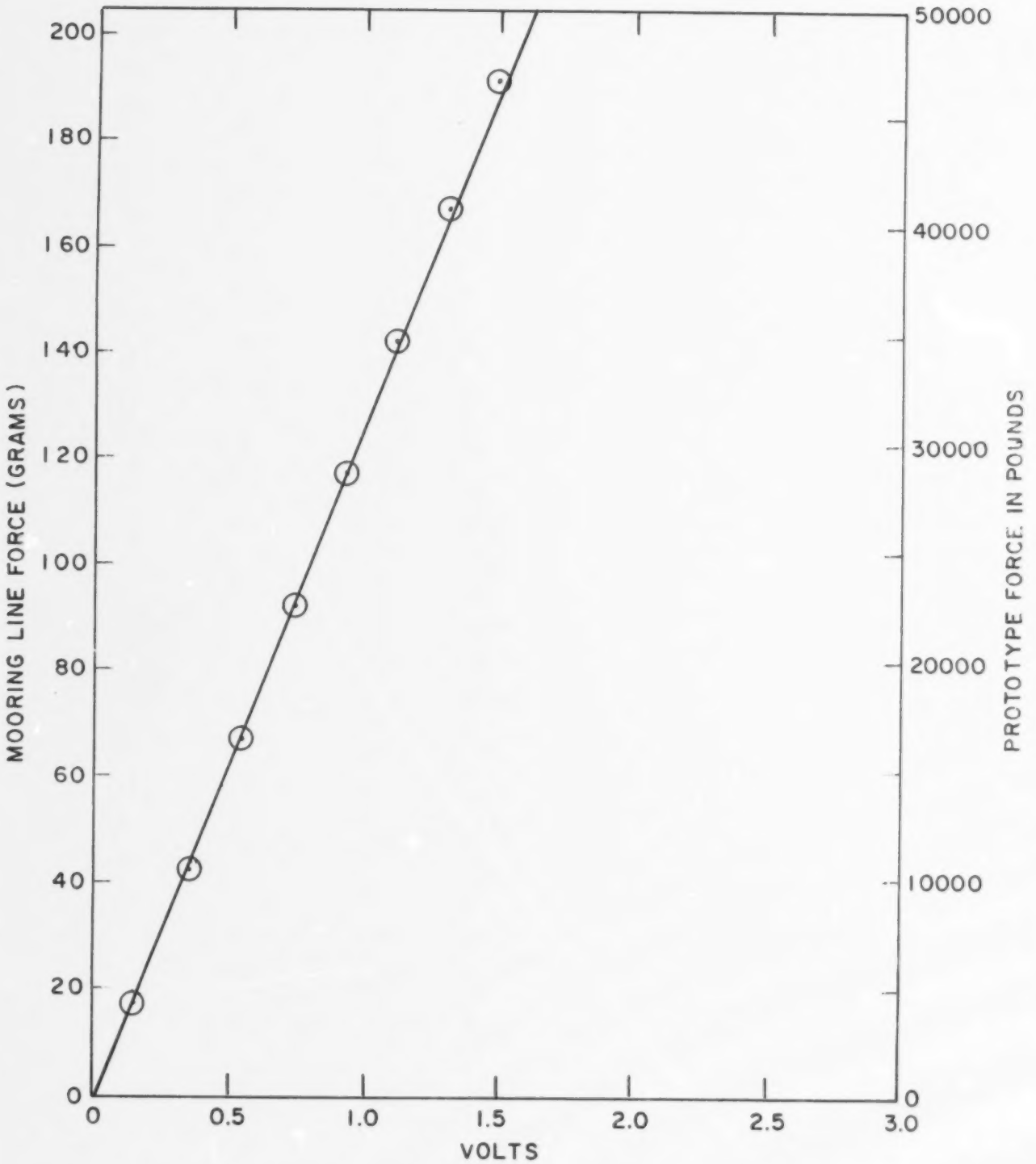


FIG.20 CALIBRATION OF DCDT FORCE TRANSDUCER FOR STERN STARBOARD BREAST LINE

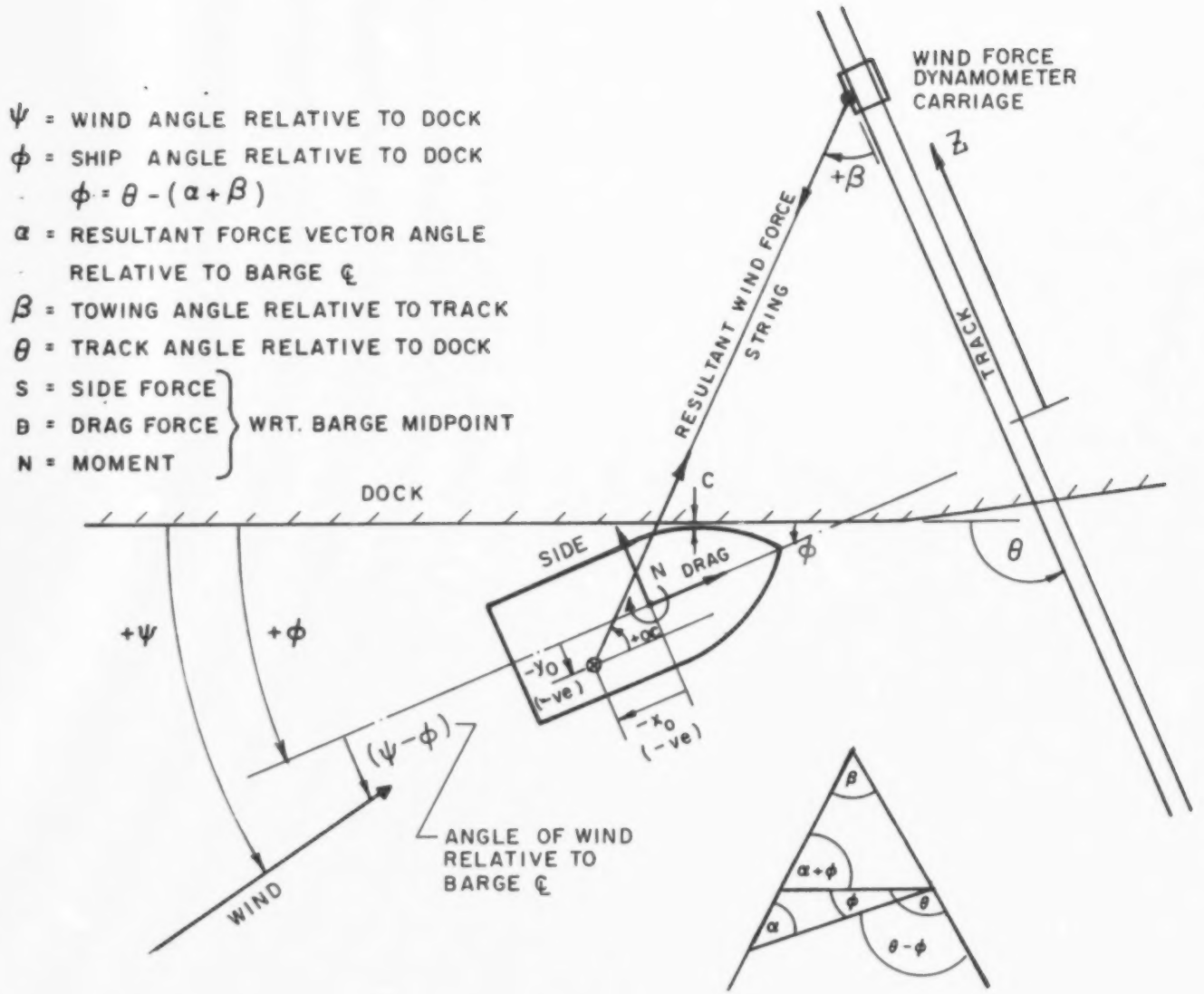


FIG.21 SIGN CONVENTION FOR LOCATING STRING TO PRODUCE CORRECT RESULTANT WIND FORCE AND MOMENT ON BARGE